Three Essays on Integrated Fiscal and Climate Policy

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Abstract

Climate change poses numerous challenges to governments and political decision makers ranging from the implementation and enforcement of environmental regulations to funding of research into green technologies and management of the transition process into a carbon-neutral economy. Since emission taxes, public investments in adaptation and public spending on research and development are not revenue-neutral, climate policy also causes fiscal effects. Especially when countries are debt-constrained, it is imperative to determine whether climate policy requires further public borrowing or, instead, relieves the budget by tapping into new sources of public funding. Therefore, this dissertation analyzes the interactions between the public budget constraint, debt and climate policy interventions from a theory-based, integrated fiscal-climate perspective. First, I examine how optimal public debt in a tax-smoothing framework is affected when the government levies an emission tax on the consumption of a polluting public good. If emissions accumulate as a persistent stock pollutant, it is generally not optimal to charge constant tax rates and abide by a balanced-budget rule. Second, I conduct a political economy analysis of strategic incentives to issue public debt if politicians compete for office and disagree on the optimal degree of pollution internalization. In contrast to political economy models neglecting stock pollution, strategic incentives caused by voting uncertainty can result in welfare gains by improving budget efficiency and reducing spending on polluting goods. Finally, I analyze how optimal emission taxes and firm-level abatement in a market with imperfect competition are affected when the public budget constraint and durable public abatement spending are considered. In this case, the government can obtain welfare improvements when substituting firm-level abatement with deficit-funded public abatement investments. Hence, climate policy is associated with normative as well as positive incentives to deviate from a balanced budget. Both aspects have to be taken into account when defining effective budget institutions.

Keywords: abatement, adaptation, environmental externality, emission tax, monopoly, political economy, pollution internalization, public debt, public good provision, stock pollution, tax smoothing, voting

Zusammenfassung

Der Klimawandel stellt Regierungen und politische Entscheidungsträger:innen vor eine Vielzahl von Herausforderungen, wie etwa die Festlegung und Durchsetzung von Umweltregulierungen, die Finanzierung von Forschung in grüne Technologien und die Steuerung des Übergangsprozesses in eine klimaneutrale Wirtschaft. Da Emissionssteuern, öffentliche Investitionen in Emissionsvermeidung und Adaption sowie Ausgaben für Forschung und Entwicklung nicht ausgabenneutral sind, hat Klimapolitik häufig auch direkte Auswirkungen auf den Staatshaushalt. Insbesondere in angespannten Finanzlagen ist daher entscheidend, ob klimapolitische Maßnahmen über Verschuldung finanziert werden müssen oder den Haushalt durch Steuererträge aus zuvor unbesteuerten Einnahmequellen entlasten werden kann. Die vorliegende Arbeit analysiert deshalb die möglichen Interaktionen zwischen finanz- und klimapolitischen Zielen mit Hilfe integrierter, theoretischer Modelle. Im ersten Abschnitt wird untersucht, wie sich die optimalen Verschuldungsregeln in einem Steuerglättungsmodell verändern, wenn der Staat eine Emissionssteuer auf private Konsumgüter erheben kann. Aufgrund der hohen atmosphärischen Lebensdauer von Emissionen sind Forderungen nach einem ausgeglichenen Staatshaushalt im Allgemeinen nicht wohlfahrtsmaximierend. Im Weiteren werden strategische Verschuldungs- und Verschmutzungsanreize für die amtierende Regierung in einem politökonomischen Modell mit Wahlunsicherheit analysiert. Im Gegensatz zu Modellen, welche persistente Verschmutzung ignorieren, können strategische Anreize in diesem Rahmen durch effizientere Verschuldungspolitik und niedrigere Emissionen zu einem Wohlfahrtsgewinn führen. Abschließend werden die Effekte der staatlichen Budgetbeschränkung und öffentlicher Investitionen in Emissionsvermeidung auf eine Emissionssteuer im unvollkommenen Wettbewerb betrachtet. Hier zeigt sich, dass im Optimum firmenseitige Vermeidung teilweise durch öffentliche Investitionen ersetzt werden sollte. Schuldenfinanzierte Ausgaben sind effizient, wenn die Vermeidungstechnologie langlebig ist und nur graduell abgeschrieben wird. Bei der Ausgestaltung effektiver Budgetinstitutionen sollte folglich berücksichtigt werden, dass Entscheidungsträger:innen sowohl normativen als auch positiven Anreizen unterliegen, von einem ausgeglichenen Haushalt abzuweichen.

Schlüsselwörter: Adaption, Emissionssteuer, Emissionsvermeidung, Internalisierung, Medianwähler:innen, Monopol, Umweltexternalität, Öffentliche Verschuldung, persistente Verschmutzung, Politökonomie, Öffentliche Güter, Steuerglättung

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Rechtliche Erklärung

Hiermit versichere ich, dass ich die vorliegende Dissertation selbstständig und ohne unzulässige Hilfsmittel verfasst habe. Die verwendeten Quellen sind vollständig im Literaturverzeichnis angegeben. Die Arbeit wurde noch keiner Prüfungsbehörde in gleicher oder ähnlicher Form vorgelegt.

Berlin, 19. April 2022

Maximilian Kellner

Contents

List of Figures vii

List of Tables vii

1 Introduction 1

1.1 General Introduction . . . 1

1.2 Previous Literature . . . 3

1.3 Outline of the Dissertation . . . 7

1.3.1 Chapter 2: Climate Policy and Optimal Public Debt in the Tax Smoothing Framework . . . 7

1.3.2 Chapter 3: Emissions and Strategic Debt under Reelection Uncertainty . . . 8

1.3.3 Chapter 4: Durable Public Abatement and Optimal Debt under Imperfect Competition . . . 9

2 Climate Policy and Optimal Public Debt in the Tax Smoothing Framework 11

2.1 Introduction . . . 11

2.2 Model . . . 15

2.2.1 Private Sector . . . 15

2.2.2 Government . . . 16

2.3 Optimal Tax and Debt Policy . . . 18

2.4 Adaptation to Climate Change . . . 24

2.5 Conclusion . . . 29

2.6 Appendix . . . 30

2.6.1 Determinant of the bordered Hessian of (2.7)–(2.11) . . . 30

2.6.2 Proof of Proposition 2.1 . . . 31

2.6.3 Proof of Proposition 2.2 . . . 31

2.6.4 Details on the numerical examples in Table 2.2 . . . 33

2.6.5 Proof of Proposition 2.3 . . . 34

2.6.6 Proof of an interior solution with respect to welfare-maximizing adaptation . . . 34

2.6.7 Proof or Equation (2.21) and Proposition 2.4 . . . 35

2.6.8 Additional income tax with collection cost . . . 37

3 Emissions and Strategic Debt under Reelection Uncertainty 39
3.1 Introduction . . . 39
3.2 Model . . . 43
3.3 Social planner's problem and certain reelection . . . 46
3.4 Recursive solution under reelection uncertainty . . . 49
3.4.1 Political decision in the final period . . . 49
3.4.2 Political decision in the first period . . . 51
3.4.3 Strategic effects on public debt . . . 53
3.4.4 Strategic effect on first-period provision of the polluting good 56
3.4.5 Intertemporal pollution damages under reelection uncertainty 59
3.4.6 Total welfare effect of strategic interactions . . . 61
3.5 Conclusion . . . 64
3.6 Appendix . . . 66
3.6.1 Proof of Proposition 3.1 . . . 66
3.6.2 Proof of Proposition 3.2 . . . 66
3.6.3 Proof of Proposition 3.3 . . . 68
3.6.4 Proof of Proposition 3.4 . . . 68
3.6.5 Marginal effects of θ_i on b and g_1 under certain reelection . . . 69

4 Durable Public Abatement and Optimal Debt under Imperfect Competition 71
4.1 Introduction . . . 71
4.2 Model . . . 75
4.2.1 Private firm's decision . . . 76
4.2.2 Regulator's problem . . . 77
4.3 Public abatement in the one-period model . . . 79
4.4 Durable public abatement capital . . . 82
4.5 Welfare effect of public debt . . . 84
4.6 Numerical analysis . . . 86
4.7 Conclusion . . . 90
4.8 Appendix . . . 92
4.8.1 Proof of Proposition 4.1 . . . 92
4.8.2 Proof of Proposition 4.2 . . . 93
4.8.3 Proof of Proposition 4.3 . . . 94
4.8.4 Derivation of u-shaped tax rates over depreciation rate . . . 96
4.8.5 The impact of stock pollution . . . 98

5 Concluding remarks 101

Bibliography 103

List of Figures

2.1 The Laffer curve and optimal public debt 22
2.2 Effect of adaptation on tax rates and public debt 28
2.3 Relationship between marginal damages and optimal tax rates 32

3.1 Level of public debt under certain reelection 49
3.2 Public budget balance at the end of the first period 55
3.3 Provision of polluting public good in the first period 58
3.4 Total welfare loss from pollution 61

4.1 Welfare-maximizing outcomes for various policy regimes and depreciation rates 87
4.2 Welfare-maximizing outcomes with persistent stock pollution 99

List of Tables

2.1 Central mechanism of emission taxation in the tax smoothing framework 12
2.2 Numerical examples for optimal emission tax and debt policies 23

3.1 Numerical comparison of first-best, certain reelection and uncertainty 63

4.1 Numerical solutions for various policy regimes and depreciation rates 89

Chapter 1

Introduction

1.1 General Introduction

Public finance is concerned with the analysis of both sides of the public budget sheet – public spending and revenues. In market economies with predominantly privately owned firms, the most important sources of public revenues generally are taxation and debt accumulation by issuing bonds. While some countries are still recovering from the fiscal burden of the financial crisis of 2008, the outbreak of the Covid-19 pandemic is exerting additional pressure on national budgets through lower tax revenues, higher unemployment, rising health care expenditures and large-scale subsidy programs. Even before the second major wave of Covid-19 infections, the OECD-countries' sovereign debt-to-GDP ratio was predicted to rise to 86 percent which amounts to a 13.4 percentage points increase in 2020 alone, exceeding the total increase during the financial crisis from 2007 to 2009 (OECD, 2020). In the US, the federal deficit tripled to USD 3.1 trillion in the fiscal year 2020 as compared to the previous period – the vast majority of the increase being directly attributed to higher expenses in response to the pandemic (CBO, 2020).

Next to tightening budgets and spending constraints, climate change remains one of the most pressing issues of policy making in the early 21st century. Governments have to take immediate and decisive measures if global warming is to be contained below the 2°C target set by the Paris Agreement (IPCC, 2018). While Glanemann et al. (2020) recently show that this emission target minimizes the economic costs of climate change, estimates also suggest that stringent climate policy measures can entail non-negligible welfare costs (see for instance Paltsev et al., 2009). On the one hand, climate change leads to a lower overall productivity which directly affects tax revenues but also increases disaster response expenditures due to more frequent and severe extreme whether events. On the other hand, uncompromising climate regulations may also reduce output and growth in polluting industries which, again, entails lower tax revenues despite costly public abatement and transition efforts.

In light of these observations, the question arises whether climate policy can help consolidate the public budget or rather increases the burden of already debt-constrained countries. Until recently, the literature has analyzed public debt from a fairly general perspective without a particular focus on environmental issues like climate change. However, the unique properties of climate change – particularly, the persistent and partially irreversible damages caused by greenhouse gas emissions – affect the timing of public abatement spending and optimal tax schedules. Furthermore, climate policy instruments, such as emission taxes and emission permit trading systems, differ from traditional sources of public funding as they are not purely distortionary, yet, may harbor considerable potential for raising public revenues. For instance, the European emission trading scheme alone is expected to raise EUR 46.8 billion in 2022 (European Commission, 2021). While these revenues may be refunded to households and firms in order to increase public acceptance, they can also fund 'green spending' or be recycled in the general public budget and, thereby, enable the government to cut purely distortionary taxes on labor or firm profits. On the other side of the public balance sheet, subsidies for transitioning to green technologies or abatement should also be assessed for their feasibility from a fiscal perspective. Governments across the globe increasingly take direct measures in response to climate change, including investments in research and development of renewable energies or carbon capture and storage technologies, adaptation to less favorable environmental conditions through the introduction of resilient tree and crop species, ground water management or large-scale construction efforts such as sea walls. Those measures generally require considerable (upfront) public funding over an extended time frame which buttresses the question of financing.[1]

Against this background, my dissertation contributes to the emerging strand of the literature dedicated to an integrated analysis of government funding, expenditures and climate policy by addressing the following three questions. First, what is the effect of climate policy on optimal public debt? Second, how are strategic incentives to issue public debt affected by greenhouse gas emissions in a voting economy? Third, can earmarking emission tax revenues for public abatement improve efficiency in a polluting industry with imperfect competition? To investigate

[1]For example, Krebs and Steitz (2021) estimate a need for climate related public investments of up to EUR 460 billion in Germany between 2021 and 2030. This amounts to nearly five percent of the total public expenditures over the same period.

these questions, I introduce emissions and pollution damages in partial-equilibrium models of public debt and taxation. All subsequent chapters examine a small open economy which issues bonds on the international capital market and can be committed to fully repay its outstanding debt. Chapter 2 examines emission taxes on a polluting consumption good with an emphasis on funding public spending requirements and its effect on public debt from a normative stance. Emission tax revenues will not necessarily reduce optimal debt. Instead, the impact on the public budget balance depends on the time path and relative severity of emission damages. Chapter 3 analyzes the strategic incentives for policy makers to issue debt in the presence of reelection uncertainty and climate change. While voting always causes a debt inefficiency when stock pollution is neglected, I employ the integrated model to show that disagreement on the optimal emission internalization rate can lead to more efficient public debt and welfare-improving emission abatement in comparison to the outcome under certain reelection. Chapter 4 still considers public debt as a fiscal policy instrument, yet, it primarily focuses on the interactions between emission taxation, firm-level and public abatement. When producers of a polluting private good exert market power, I find that the government should partially substitute emission taxation for public abatement to reap a welfare gain.

All three chapters suggest that whether climate policy mandates higher or lower public debt is contingent on a number of normative and positive reasons. At the same time, adhering to a balanced budget rule is generally not optimal in any of the frameworks which will be subsequently analyzed.

1.2 Previous Literature

The individual chapters of this dissertation are related to various influential contributions from either the fields of public debt theory or optimal emission taxation.

A considerable strand of the fiscal policy literature analyzes the normative role of public debt. In classical economic theory, the Ricardian Equivalence Theorem suggests that public debt is welfare-neutral in the long run (see Barro, 1989). Households anticipate that increased public spending or tax reliefs in the present have to be covered by higher taxation in the future and adapt their saving schedules accordingly. As a result, total investments remain unchanged such that the interest rate also stays constant regardless of the stock of public debt. In modern theory, this theorem has been re-evaluated and challenged repeatedly. Most relevant in the context of Chapter 2 is the approach by Barro (1979, 1989), who argues that the equivalence result only applies to non-distortionary lump-sum taxation. In his tax-smoothing framework, Barro (1979) derives that positive or negative levels of public debt can be justified from a normative perspective if taxes are distortionary and public spending fluctuates over time.

Furthermore, the positive theory on public debt provides ample insight on the political economy incentives underlying public deficits. Seminal contributions to this area are the 'partisan preferences' approach by Persson and Svensson (1989) and Alesina and Tabellini (1990) as well as the median voter model by Tabellini and Alesina (1990). In a voting economy, strategic incentives to issue inefficiently high debt can occur when politicians are only interested in their voters' utility instead of the entire population's welfare. In the conventional framework, conservative proponents of a 'slim' state compete for office against a 'socialist' party which prefers high public expenditures. If the conservatives anticipate that the socialists could take office in the next legislative period, they accumulate excessive public debt forcing their successor to service debt in the next period instead of increasing public spending. In Chapter 3, I draw on this approach and expand it by introducing diverging preferences for climate action across parties. The 'war of attrition' theory by Alesina and Drazen (1991) provides another explanation of strategic debt accumulation under voting. When politicians bargain over who has to pay for public expenditures, there is an incentive to issue public debt and 'push off' the decision into the future until one party concedes and agrees to account for the majority of outstanding debt. The longer bargaining takes to resolve, the larger becomes the inefficiency associated with debt and interest accumulation. In addition to the theoretical models above, Woo (2003) provides empirical evidence for the effects of institutions, political stability and administrative centralization on the level of public debt.

However, the existing normative and positive literature on public debt generally ignores environmental or climate related issues and, thus, is not well equipped to answer the three focal questions stated above. Therefore, this dissertation also builds on concepts form environmental economics, particularly the literature analyzing taxes on negative environmental externalities. Pigouvian taxation provides a well-established principle to effectively address this issue. By levying a tax rate equal to the marginal damage caused by the externality, the regulator can unilaterally restore the first-best solution even in cases with a large number of involved actors where other solutions, such as Coasian bargaining, would fail due to prohibitively high transaction costs (Baumol, 1972). However, Buchanan (1969) argues that the Pigouvian tax rate is no longer optimal when a polluting industry is not perfectly competitive. Chapter 4 largely builds on the contribution by Barnett (1980), who formalizes and extends Buchanan's argument in a monopoly model. The literature based on Downing and White (1986), Milliman et al. (1989) and Requate and Unold (2001, 2003) is also relevant when determining the optimal emission tax rate. This strand of the literature focuses on the government's ability to induce firm-level abatement and technology transition through the choice of an appropriate emission tax schedule. When technology adoption joins emission internalization on the public agenda, the optimal tax rate may also deviate from the Pigouvian level. While these contributions provide a framework for my analysis, they generally neglect that emission tax revenues can influence the public budget and, thereby, public debt.

This interaction between fiscal and climate policy is analyzed by the double-dividend literature building on contributions by Bovenberg and De Mooij (1994), Proost and Van Regemorter (1995), Parry (1995) and Goulder (1995) which acknowledge the revenue-raising capabilities of emission taxes. A double dividend is earned when an emission tax does not only benefit its environmental objective – which represents the first dividend – but also generates a second dividend via the effect of emission tax revenues on the public budget. If lump-sum levies are infeasible, the government traditionally has to resort to purely distortionary taxation of, e.g., income or firm profits to meet its budget requirements for public spending. By recycling emission tax revenues in the public budget, it can be possible to cut these purely distortionary taxes and improve overall welfare. This theory is relevant to both Chapters 2 and 4. Yet, my analysis emphasizes the role of emission tax revenues for public debt and public abatement expenditures instead of the effect on other taxes which is not investigated by the double-dividend literature.

While these seminal contributions are highly influential for the subsequent analytical models, they can be clearly sorted either into the realms of environmental economics or public debt analysis. Since my research questions focus on the interrelations between taxation, public spending, debt and environmental or climate regulation, this dissertation contributes to the recent strand of the literature on integrated fiscal-climate policy. A limited number of theoretical contributions already address this topic. Notably, Fodha and Seegmuller (2014) find that governments should invest in abatement, while decreasing the stock of public debt in order to avoid a poverty trap due to an insufficiently small capital stock. In contrast to my subsequent analysis, they assume that a non-distortionary lump-sum tax is available to raise revenues in addition to debt accumulation, yet, do not consider an internalizing emission tax. Furthermore, in a recent working paper, Boly et al. (2019) interpret pollution as 'environmental debt' in an analogy to monetary or fiscal debt. They show that both types of debt are substitutes in the short-run as environmental interventions can be funded by bond issuing. This relationship is inverted in the long-run due to the excess burden of servicing public debt. Employing an overlapping generations model, Andersen et al. (2020) examine the effects of emission taxation and public abatement on intergenerational justice in the light of the Pareto criterion. In their model, pollution from present production only affects the welfare of future generations. Hence, they find that climate policy initially has to be debt-funded to ensure that the current generation is not worse off due to political intervention. Emission taxation can gradually replace debt-funded abatement as environmental quality improves. All three papers assume a normative perspective and neither examine the dual role of emission taxation in the presence of other public spending objectives nor political economy incentives.

The macroeconomic evidence on integrated fiscal-climate issues from numerical analyses is already more complete. For instance, Economides and Xepapadeas (2018) employ a dynamic stochastic general equilibrium (DSGE) model to simulate the effect of productivity shocks caused by climate change on key characteristics of the economy including public debt. While these authors do not consider climate policy interventions, Annicchiarico and Di Dio (2015) also conduct a DSGE analysis to show how emission caps interact with monetary policy. However, both papers merely include public debt as a degree of freedom in the equilibrium conditions with no particular emphasis on bond issuing behavior and the related effects on tax smoothing, public abatement or strategic debt accumulation. Interactions between countries on the international capital market are examined in a recent study by Catalano et al. (2020). In an overlapping generations model with capital depreciation shocks due to extreme weather events, they find that debt-constrained countries should be granted debt reliefs in order to fund public investments in adaptation technologies. By only allowing for taxation of labor, capital and consumption, their analysis cannot examine the dual role of emission taxation that is central to my dissertation.

While the number of working papers on the integrated analysis of fiscal and climate policy has been growing over the past years, the theoretical foundation of this literature is still rather narrow. To the best of my knowledge, the effects of interactions between public debt and environmental policy in tax-smoothing or political economy frameworks have not yet been studied previously. Likewise, most of the existing studies in this area do not model distortionary or corrective taxes as sources of public revenues. Therefore, the goal of this dissertation is to contribute to bridging the gap between fiscal and environmental economics with a particular focus on public debt and expenditures.

1.3 Outline of the Dissertation

1.3.1 Chapter 2: Climate Policy and Optimal Public Debt in the Tax Smoothing Framework

The first chapter of this dissertation presents findings from a joint paper with Marco Runkel. In this contribution, we re-asses the tax-smoothing rule for optimal public debt developed by Barro (1979; 1989) in the face of environmental pollution. If the government levies a distortionary tax with the sole objective to raise public revenues, Barro (1979) shows that in order to minimize the excess burden of taxation and, thereby, maximize welfare, the optimal tax rate has to remain constant across all periods. This result implicitly defines the optimal level of public debt. On the one hand, the government should not maintain a balanced budget if spending requirements vary across time. On the other hand, whenever public expenses are constant, this framework lends no justification for a positive level of public debt and, rather, mandates a balanced budget.

In our analysis, we examine how Barro's findings are affected by taxes that are not solely collected to raise revenues but serve a dual purpose. In our framework, the government imposes an emission tax on the consumption of a polluting private good in order to internalize the associated welfare loss from environmental damages. It is well-known that this tax should be equal to the marginal damage, i.e. the Pigouvian level, if its only objective is to restore the efficient amount of pollution. In the context of climate policy, the welfare loss depends on the persistent stock of pollution rather than just the flow of emissions per period. Since greenhouse gases typically decay at a low rate, earlier emissions tend to be more harmful in the sense that cumulative marginal damages are larger for earlier than for later emissions. In this case, the optimal first-period tax rate should exceed the second-period tax rate such that the government deviates from the tax-smoothing principle.

How this affects optimal public debt is contingent on the tax rates' locations on the Laffer curve. For rather high marginal damages, the tax rates would be on the decreasing side of the Laffer curve which implies that tax revenues are higher in the second period. Thus, it is optimal to deviate from the balanced budget path and issue public debt even if spending requirements are constant over time. Conversely, for tax rates on the increasing side of the Laffer curve and constant spending requirements, emission tax revenues are higher in the first period and the government should accumulate public savings. These effects are inverted if the cumulative marginal damages increase over time as this warrants a higher tax rate in the second than in the first period. Hence, the central insight we derive from our analysis is that climate policy can either increase or decrease the optimal level of public debt. However, a balanced budget is no longer optimal in the presence of stock pollutants even if all other factors remain constant over time.

We further extend our analysis by introducing public adaptation investments to increase the economy's resilience to climate change. Additional expenses for adaptation should be distributed evenly across all periods to reduce its distortionary impact on welfare. Moreover, the marginal damage of emissions decreases with higher adaptation efforts, also attenuating the emission internalization incentive. Both effects imply that the tax-smoothing objective gains weight in the trade-off faced by the government when deciding on the emission tax rates.

1.3.2 Chapter 3: Emissions and Strategic Debt under Reelection Uncertainty

In this chapter, based on a single-authored paper, I address political economy effects caused by voting uncertainty. Strategic interactions between the future and present government arise whenever the incumbent cannot be certain of reelection in the next period. In an influential study, Tabellini and Alesina (1990) show that the incumbent government faces the incentive to issue an inefficiently high level of public debt if parties or voters, respectively, disagree on the optimal composition of public good provision. In this chapter, I expand on their model by assuming that provision of one public good also contributes to a persistent stock of pollutants. This creates an additional channel through which present and future decision makers interact.

In a bipartisan economy, two parties compete for office at the beginning of each period. The politician who is currently in office decides on how to distribute the public budget between a clean and the polluting public good. While Tabellini and Alesina (1990) assume that each party prefers a different bundle of public goods, politicians do not agree on the optimal degree of pollution internalization in my model. For instance, an environmentalist party, fully internalizing pollution damages, might run against an industrialist party ignoring the externality and, thus, providing more of the polluting good than optimal from the environmentalists' perspective. Disagreement on the optimal provision of public goods implies that the incumbent tries to limit the future government's spending discretion to hedge for the case that the incumbent is not reelected. When the future government is committed to repay any outstanding debt, the incumbent strategically increases borrowing. By draining funds from the future budget, the present government can spend more on their preferred public goods bundle, thereby, increasing their (electorate's) welfare. At the same time, the future budget is reduced by outstanding debt such that spending capabilities are effectively curbed by the incumbent's strategic decision. Hence, voting uncertainty leads to higher public debt in comparison to a scenario where the incumbent is reelected with certainty.

Persistent pollution affects this result in three ways. First, similar to the findings in Chapter 2, there is a normative incentive to deviate from a balanced budget and issue public debt or accumulate public savings depending on how quickly emissions decay. Hence, unlike in the underlying model by Tabellini and Alesina (1990), strategically increasing public debt due to voting uncertainty does not necessarily lead to a budget inefficiency but can improve welfare if the incumbent would issue inefficiently few bonds under certain reelection. Second, as the future government not only inherits its predecessor's debt but also the stock of pollution, an additional emission interaction occurs which can further improve welfare. Leaving a large stock of pollutants to the successor causes under-provision of the polluting good or excessive pollution damages in the future and is not favorable from any incumbent's perspective. For this reason, politicians face an incentive to reduce emissions in the present period. This leads to the central result of this chapter that any incumbent politician chooses to abate pollution regardless of their environmental preferences. Third, if industrialists initially hold office and are superseded by the environmentalist party, second-period emissions and, thereby, total pollution damages also decrease. Since all three effects can lead to more efficient outcomes under uncertainty, the voting scenario may even become superior to the certain reelection outcome. Therefore, the integrated fiscal-climate analysis qualifies the findings from the purely fiscal models by Persson and Svensson (1989), Alesina and Tabellini (1990) and Tabellini and Alesina (1990), who conclude that, from a perspective centered on budget efficiency, certain reelection is always preferable to voting with uncertain outcomes. In my analysis, even if reelection uncertainty results in a budget inefficiency, it can still be outweighed by environmental gains.

1.3.3 Chapter 4: Durable Public Abatement and Optimal Debt under Imperfect Competition

The final chapter, also based on a single-authored paper, emphasizes the role of emission taxation on the abatement and production decisions of a monopolistic firm when the state can also engage in emission abating activities. The analytical framework of this chapter follows the seminal contribution by Barnett (1980), who examines the impact of imperfect competition on the Pigouvian tax rate. Barnett (1980) shows that, if the welfare loss from imperfect competition outweighs marginal environmental damages, it can be optimal to subsidize production of the polluting private good instead of implementing a positive emission tax. While the standard model follows the simplifying assumption that tax revenues are redistributed as a lump-sum transfer and spent in a welfare-neutral fashion, empirical evidence emphasizes that tax revenues should create a direct benefit for households in order to foster the public acceptance of emission tax programs (e.g., Beiser-McGrath and Bernauer, 2019 or Carattini et al., 2019).

Therefore, I expand Barnett's framework by assuming that emission tax revenues are earmarked for either investments in a public abatement technology or provision of a public consumption good (e.g., a climate dividend) which benefits households. When public spending is no longer restricted to lump-sum transfers, the regulator's optimal emission tax scheme does not only depend on the objectives to internalize emissions and correct the monopolistic distortion, but is also driven by revenue-raising incentives which counters under-internalization stemming from imperfect competition. Moreover, as the central finding of Chapter 4, it is always optimal to cut the emission tax rate and invest in public abatement. By substituting public abatement for emission taxation, the regulator reaps a double dividend. On the one hand, public abatement directly reduces environmental damages. On the other hand, a lower emission tax provides an incentive for the monopolistic firm to increase output which improves production efficiency in the private good market. This is also associated with higher emissions in the private sector which are cushioned by public abatement. Since a tax cut can be associated with lower revenues, public abatement has to be funded at the expense of decreased spending on other public goods.

In the second part of Chapter 4, I examine how this result is affected if public abatement capital is durable. Thereby, I acknowledge that – due to a lower exposure to business cycle fluctuations and potentially higher patience – a public regulator may have access to abatement technologies, such as afforestation, which prove ineffective for the private sector. Durability reinforces the incentive to invest in public abatement in the first period which puts additional stress on the public budget. Depending on the valuation of general public good provision, this can force a tax raise when the government has to abide by a balanced budget rule even tough public abatement is a substitute for emission taxation. Hence, by issuing public debt, the fiscal burden of large early investments can be distributed more evenly across all periods which improves welfare.

Chapter 2

Climate Policy and Optimal Public Debt in the Tax Smoothing Framework

2.1 Introduction[2]

The substantial social and economic costs of environmental degradation caused by climate change have been thoroughly detailed, amongst others, by Tol (2002a, 2002b) and Stern (2008). For this matter, it should be of little surprise that the problem of global warming is one of the most prominent topics in the current political debate. In recent years, it became apparent that governments have to take measures to both mitigate, i.e., decelerate climate change, and adapt, i.e., brace the economy against the consequences of altered, less favorable environmental conditions (see, e.g., the Paris Agreement in United Nations, 2015). Notably, the discussion on climate policy design often shifts to questions of financing and, thus, the impact of climate policy on the public budget balance. On the one hand, there is hope for co-benefits, for instance, when revenues from carbon pricing enable the decision maker to cut distortionary taxes on labor or capital (see, e.g., Goulder, 1995, and Proost and Van Regemorter, 1995, for the 'double dividend' theory) or public debt. On the other hand, investments in adaptation technologies or subsidies towards renewable energy production are generally expensive and put additional strains on the public budget. These effects are of particular relevance, as countries worldwide struggle with the sustainability of public finance in the wake of the Great Recession and the

[2]The contents of this chapter are based on M. Kellner and M. Runkel (2021) 'Climate Policy and Optimal Public Debt' which was previously made available as *CESifo working paper no. 8865*.

Covid-19 pandemic.

This chapter contributes to the discussion on the fiscal implications of climate policy. We investigate the rather unexplored but – as argued above – highly policy relevant relation between emission taxation and public debt. In doing so, we take a normative point of view and address the following research question: when a tax is implemented not only to satisfy public spending requirements, but also to lower greenhouse gas emissions and internalize the associated environmental externality, will it create incentives to decrease or increase the *optimal* level of public debt? At first glance, one might conjecture that taking into account the internalization of environmental externalities will create additional tax revenues that can be used to lower optimal public debt. However, the central insight of our analysis is that the impact of the environmental externality on optimal public debt may be of either sign, depending on whether the cumulative marginal environmental damages caused by one unit of emissions are decreasing or increasing over time and whether the optimal tax rates are on the increasing or decreasing side of the Laffer curve.

In order to derive this result, we employ Barro's tax-smoothing approach (Barro, 1979 and 1989) and adapt it to suit our requirements by introducing environmental externalities. We develop a two-period model, where a representative household consumes two goods in each period, one of which pollutes the environment. Emissions are assumed to accumulate over time as a stock and cause environmental damage. The household pays an emission tax upon consumption of the polluting good. The tax fulfills a dual role by, first, internalizing an environmental externality and, second, providing funds for exogenously given public expenditures. In addition, in the first period, spending requirements can be met through issuing public debt which has to be repaid in the second period. Emission tax rates and public debt are set such that the household's welfare is maximized.

For a better understanding, the detailed results arising from our analysis are visualized in Table 2.1.

Table 2.1: Central mechanism of emission taxation in the tax smoothing framework

cumulative marginal damages	optimal tax rates	optimal revenues and debt if τ_1 and τ_2 on ... ... increasing side of Laffer curve	... decreasing side of Laffer curve
$\mathrm{MD}_1 = \mathrm{MD}_2 = 0$	$\tau_1 = \tau_2$	$R_1 = R_2$ ⇒ tax smoothing by optimal debt b	
$\mathrm{MD}_1 > \mathrm{MD}_2 > 0$	$\tau_1 > \tau_2$	$R_1 > R_2$ ⇒ negative effect on optimal b	$R_1 < R_2$ ⇒ positive effect on optimal b
$0 < \mathrm{MD}_1 < \mathrm{MD}_2$	$\tau_1 < \tau_2$	$R_1 < R_2$ ⇒ positive effect on optimal b	$R_1 > R_2$ ⇒ negative effect on optimal b

MD_t=cumulative marginal damages from period t consumption; τ_t = optimal tax rate in period t; R_t = optimal tax revenue in period t; b = optimal public debt in period 1; $t = 1, 2$

As a benchmark, we first consider the case without an environmental externality, i.e., without marginal damages. In this case, optimal tax rates remain constant over time in order to minimize the present value of the excess burden associated with taxation. Constant tax rates imply constant tax revenues and, thus, optimal public debt is positive [negative] only if the expenditure requirement is larger [smaller] in the first period than in the second period. This represents the traditional tax-smoothing argument of public debt derived by Barro (1979, 1989). Starting from this benchmark, we find that introducing an environmental externality may induce the optimal policy to deviate from tax smoothing. If the cumulative marginal environmental damages from first-period consumption are larger [smaller] than those from second-period consumption, the first-period tax rate will be higher [lower] than the second-period tax rate as the internalization incentive is stronger [weaker] in the first period. In addition, if both tax rates are on the increasing side of the Laffer curve, tax revenues in the first period are larger [smaller] than those in the second period. Compared to the tax-smoothing level, we therefore obtain a negative [positive] effect on the optimal level of public debt. For example, if spending requirements are constant over time, optimal public debt becomes negative [positive]. This implication is inverted if both tax rates are on the decreasing side of the Laffer curve. Then, tax revenues are larger [lower] in the second period and we obtain a positive [negative] effect on the optimal level of public debt. We show that these results hold independently of whether tax revenues from Pigouvian internalization of the environmental externality are already sufficient to finance the spending requirements or whether optimal tax rates need to deviate from the Pigouvian level as well as when the government can raise an additional income tax associated with collection costs.

As an extension, we also take endogenous adaptation investments into account. In this case, the decision maker can choose to invest in a technology which requires upfront effort in the first period and adapts the economy to better cope with pollution in the second period. Thus, we further extend the model by adding an endogenous margin to public spending, while the standard tax-smoothing analysis of Barro (1979, 1989) takes spending requirements as exogenously given. Since adaptation investments alleviate the environmental damages experienced from emissions, we move closer to the benchmark without environmental externalities and the optimal tax rates turn out to deviate less from the tax-smoothing principle. Hence, we find that adaptation will shrink the wedge between first- and second-period tax rates previously induced by the environmental externality. Yet, investing in the technology always creates an incentive to issue more debt in order to finance adaptation in the first period. That is, if accumulating public debt [savings] was optimal before, adaptation now leads to a higher total level of debt [lower savings].[3]

This chapter contributes to the literature in two ways. First, we add an additional dimension to the discussion on the fiscal implications of climate policy. As already mentioned above, the double dividend is a prominent topic in this strand of the literature, see e.g., Bovenberg and De Mooij (1994), Proost and Van Regemorter (1995), Parry (1995) and Goulder (1995). This literature generally addresses the question whether an emission tax – in addition to its positive effect of increasing environmental quality by reducing emissions – can also improve the efficiency of the tax system by reducing other distortionary taxes. A related topic is discussed in the recent study by Franks et al. (2017). In a dynamic general equilibrium model, these authors investigate whether emission taxation attains a higher welfare level than taxation of mobile capital, even if environmental externalities are ignored. However, none of these papers examines the link between emission taxation and optimal public debt, which is the main contribution of our analysis.

Second, This chapter introduces the issue of climate change into the literature on public debt. The existing literature can basically be divided into positive studies explaining the accumulation of public debt, like the political economy models of, e.g., Persson and Svensson (1989), Tabellini and Alesina (1990) and Woo (2003), and normative studies investigating optimal public debt, like the tax-smoothing theory by Barro (1979, 1989). Our analysis relates to the normative approach and, as already stated above, shows that in the presence of a taxable, polluting consumption good, the optimal public deficit may be non-zero even if spending requirements are constant over time. To the best of our knowledge, studies that explicitly investigate the relation between public debt and environmental issues are scarce in the debt literature. Some exceptions are Fodha and Seegmuller (2014), who examine the welfare effect of an environmental abatement policy which may either be funded via tax revenues or public debt in a fully dynamic model finding that pollution abatement should not be conducted at the costs of increased debt when the capital stock is low. In a model without emission taxation, Catalano et al. (2020) investigate the impact of fiscal policy on public adaptation investments in a

[3] As a remark, note that the alleviating effect of adaptation on the deviation from tax-smoothing tax rates intuitively also holds if adaptation already reduces the first-period damages, and not only the second-period damages as assumed in our formal model. In this case, the model becomes more similar to the benchmark case without an environmental externality. In contrast, if adaptation requires investments not only in the first but also in the second period, again, in contrast to our formal model, the effect of adaptation on optimal debt may be reversed, if optimal adaptation investments are larger in the second period than in the first period.

multi-country setup, where they show that early debt-funded adaptation spending has a long-run beneficial effect even though negatively affecting the debt-to-GDP ratio initially. Andersen et al. (2020) focus on the intergenerational distributional effects of costly public abatement and how taxation and debt can be employed to reach an intergenerational Pareto improvement. While these papers also investigate the link between debt and environmental issues, none of them takes into account the dual role of emission taxation as a means of financing public spending and correcting externalities. Hence, in contrast to our analysis, they cannot investigate the implications of climate policy on the tax-smoothing role of public debt.

This chapter is organized as follows. In Section 2.2 we introduce the basic framework. In Section 2.3, we analyze the optimal tax and debt policy. In Section 2.4, we investigate how our findings are affected when the economy can adapt to pollution by means of investing in an adaptation technology. The final section concludes the chapter.

2.2 Model

2.2.1 Private Sector

We consider an economy with a representative household that lives for two periods, 1 and 2. In period $t = 1, 2$ the household consumes a composite good Y in quantity y_t and a polluting good X in quantity x_t. The household's utility in period t equals

$$u_t = y_t + V(x_t), \tag{2.1}$$

with $V' > 0$ and $V'' < 0$. Without loss of generality, we normalize the household's discount rate to zero, so the present value of the household's utility reads $w = u_1 + u_2$.

In each period, the household receives an exogenous endowment of a numeraire good normalized to one. We assume that goods Y and X can be produced from the endowment by a one-to-one-technology. Hence, the prices of both goods are equal to one. Good Y is untaxed, whereas good X is taxed by a unit tax with tax rate τ_t in period t.[4] The household may receive a lump-sum transfer z_t from the government in period t. For simplicity, we ignore private savings. The private budget constraint

[4] We ignore further taxes in oder to highlight the debt effects of environmental taxes and to avoid mixing up our results with those from the above-mentioned double dividend literature. Additionally, we can confirm our main findings in an extended model where the government can also levy a distortionary tax on income, if we model the deadweight loss of this tax in the stylized way introduced by the initial contribution of Barro (1979). Details are provided in Appendix 2.6.8.

in period t is

$$y_t + (1+\tau_t)x_t = 1 + z_t. \tag{2.2}$$

Tax rates and lump-sum transfers are taken as given by the household. The household chooses consumption in order to maximize the present value of its utility. Inserting (2.2) into (2.1), the maximization problem can be written as

$$\max_{x_1,x_2} w = \sum_{t=1,2} \Big\{ V(x_t) + 1 + z_t - (1+\tau_t)x_t \Big\}.$$

The first-order condition with respect to x_t reads

$$V'(x_t) = 1 + \tau_t, \qquad t = 1,2. \tag{2.3}$$

This condition equates the household's marginal utility to the after-tax price of good X in period t. Hence, the household's optimal consumption of good X in period t is a function of the tax rate in period t. Formally, equation (2.3) implies $x_t = X(\tau_t)$ with $X'(\tau_t) = 1/V'' < 0$ and $X''(\tau) = -V'''/V''^3 \geq 0$.[5]

2.2.2 Government

In addition to taxing good X, the government may raise revenues in the first period through issuing public debt b which has to be repaid in the second period. As for the private discount rate, we normalize the interest rate on public debt to zero. Public policy pursues two goals. First, revenues from taxation and debt are used to finance public spending requirements in both periods. In the basic model, we follow the tax-smoothing literature and assume exogenously given spending requirements $g_1 \geq 0$ and $g_2 \geq 0$ in both periods. Second, the government uses taxation in order to internalize the pollution externality caused by private consumption of good X. In period 1, this externality is reflected by the damage function $D_1(x_1)$ with $D_1' > 0$ and $D_1'' \geq 0$. In period 2, the damage function reads $D_2(x_2 + \gamma x_1)$ with $D_2' > 0$, $D_2'' \geq 0$ and $\gamma \geq 0$. The parameter γ allows distinguishing between flow pollution ($\gamma = 0$) and stock pollution ($\gamma > 0$). Greenhouse gas emissions and climate change provide an example for the latter case.

[5]Here, we implicitly assume $V''' \geq 0$ which is satisfied, for example, if V is quadratic or if V is monotone and has monotone derivatives. In the latter case, $V''' > 0$ is implied by $V' > 0$ and $V'' < 0$.

Formally, the government's welfare maximization problem can be stated as

$$\max_{\{b,\tau_t,z_t\}_{t=1,2}} w = \sum_{t=1,2} \Big\{ V[X(\tau_t)] + 1 + z_t - (1+\tau_t)X(\tau_t) \Big\} \\ - D_1[X(\tau_1)] - D_2[X(\tau_2) + \gamma X(\tau_1)], \tag{2.4}$$

subject to

$$\tau_1 X(\tau_1) + b = g_1 + z_1, \quad \tau_2 X(\tau_2) - b = g_2 + z_2, \tag{2.5}$$

$$z_1 \geq 0, \qquad z_2 \geq 0. \tag{2.6}$$

According to (2.4), the government maximizes the present value of the household's utility net environmental damages, taking into account the public budget constraints given in (2.5) and the household's consumption reactions determined by $x_t = X(\tau_t)$. Moreover, due to (2.6) we restrict the policy space to non-negative lump-sum transfers. The reason is that we follow the tax-smoothing literature referred to in the introduction and focus on the case where the government has to use distortionary taxation in order to meet its spending requirements. If we would allow for negative transfers, the government would have an incentive to use these transfers in order to finance the spending requirements in a non-distortionary way. Note that we nevertheless need the transfers since, in contrast to the previous tax-smoothing literature, in our framework tax revenues may exceed the spending requirements due to the government's second goal of internalizing the pollution externality. Hence, in our framework the transfers only exist in order to redistribute back potential excess revenues from the emission tax in a non-distortionary way. As shown below, (2.6) will be binding – and z_1 and z_2 will vanish – in the (most realistic) case where emission tax revenues are not sufficient to finance the public spending requirements.

The solution to the government's welfare maximization problem (2.4)–(2.6) can be characterized with the help of the Lagrangian

$$L = \sum_{t=1,2} \Big\{ V[X(\tau_t)] + 1 + z_t - (1+\tau_t)X(\tau_t) \Big\} - D_1[X(\tau_1)] - D_2[X(\tau_2) + \gamma X(\tau_1)] \\ + \lambda_1[\tau_1 X(\tau_1) + b - g_1 - z_1] + \lambda_2[\tau_2 X(\tau_2) - b - g_2 - z_2],$$

where λ_1 and λ_2 are the Lagrange multipliers associated with the budget constraint in period 1 and period 2, respectively. The Kuhn-Tucker first-order conditions read

$$
\begin{aligned}
L_b &= \lambda_1 - \lambda_2 = 0, && (2.7)\\
L_{\tau_1} &= -X(\tau_1) - \Big\{ D_1'[X(\tau_1)] + \gamma D_2'[X(\tau_2) + \gamma X(\tau_1)] \Big\} X'(\tau_1) \\
&\qquad + \lambda_1 \Big[X(\tau_1) + \tau_1 X'(\tau_1) \Big] = 0, && (2.8)\\
L_{\tau_2} &= -X(\tau_2) - D_2'[X(\tau_2) + \gamma X(\tau_1)] X'(\tau_2) \\
&\qquad + \lambda_2 \Big[X(\tau_2) + \tau_2 X'(\tau_2) \Big] = 0, && (2.9)\\
L_{\lambda_1} &= \tau_1 X(\tau_1) + b - g_1 - z_1 = 0, && (2.10)\\
L_{\lambda_2} &= \tau_2 X(\tau_2) - b - g_2 - z_2 = 0, && (2.11)
\end{aligned}
$$

and the slackness conditions are

$$
\begin{aligned}
L_{z_1} &= 1 - \lambda_1 \leq 0, \quad z_1 \geq 0, \quad z_1 L_{z_1} = 0, && (2.12)\\
L_{z_2} &= 1 - \lambda_2 \leq 0, \quad z_2 \geq 0, \quad z_2 L_{z_2} = 0, && (2.13)
\end{aligned}
$$

where in (2.8) and (2.9) we used (2.3). For the second-order conditions to be satisfied, the determinant $|H|$ of the bordered Hessian needs to be negative. We determine $|H|$ in Appendix 2.6.1 and will verify that $|H| < 0$ in all relevant cases considered below.

2.3 Optimal Tax and Debt Policy

To analyze the government's welfare maximum characterized by conditions (2.7)–(2.13), we first examine the public budget constraints (2.10) and (2.11). Adding both equations gives the government's intertemporal budget constraint

$$\tau_1 X(\tau_1) + \tau_2 X(\tau_2) = g_1 + g_2 + z_1 + z_2, \tag{2.14}$$

stating that the present value of tax revenues (LHS) has to be equal to the present value of public spending and transfers (RHS). Subtracting (2.11) from (2.10) yields

$$b = \frac{g_1 - g_2}{2} + \frac{\tau_2 X(\tau_2) - \tau_1 X(\tau_1)}{2} + \frac{z_1 - z_2}{2}. \tag{2.15}$$

In the subsequent analysis, we will use (2.15) in order to compute the optimal level of public debt. Basically, the equation has the same meaning as in previous studies on tax smoothing without pollution. The first term on the RHS shows the central tax-smoothing argument: Public debt is used to equalize variations in exogenous public spending. Without externalities, the optimal tax policy minimizes the excess burden of taxation by charging constant tax rates over time. Consequently, tax revenues also remain constant such that the second term on the RHS of (2.15) vanishes. In contrast, we will show that tax revenues may vary over time in our analysis with environmental externalities. Thus, taxation can affect the optimal debt policy via the second term on the RHS of (2.15).[6]

Specifically, if tax revenues in the second period, $\tau_2 X(\tau_2)$, are larger than tax revenues in the first period, $\tau_1 X(\tau_1)$, the second term on the RHS of (2.15) is positive, providing an additional rational for public debt. To determine tax revenues in period t associated with the tax rate τ_t, we make use of the Laffer curve defined as

$$R(\tau_t) = \tau_t X(\tau_t). \tag{2.16}$$

We impose the following quite general assumption on the shape of the Laffer curve.

Assumption A2.1 *The Laffer curve, $R(\tau)$, is twice continuously differentiable and satisfies $R'(\tau) = X(\tau) + \tau X'(\tau) \gtreqless 0$ if and only if $\tau \lesseqgtr \bar{\tau}$ with $\bar{\tau} > 0$, $R''(\tau) = 2X'(\tau) + \tau X''(\tau) < 0$, $R(0) = 0$ and $\lim_{\tau \to \infty} R(\tau) < (g_1 + g_2)/2 < R(\bar{\tau})$.*

This assumption states that the Laffer curve follows an inverted u-shape with a unique maximum at the positive tax rate $\bar{\tau}$ and vanishing tax revenues at a zero tax rate. The latter properties in Assumption A2.1 ensure that maximum revenues at $\bar{\tau}$ are more than enough to meet the spending requirements. Together with the inverted u-shape of the Laffer curve, this implies that there are additional tax rates $\tau \gtrless \bar{\tau}$ on both sides of the Laffer curve which generate sufficient revenues to fund total public spending, $g_1 + g_2$.

Next, we rewrite the first-order conditions of welfare maximization in order to identify conditions under which tax rates and revenues differ across the two periods.

[6] As stated above, in the (most realistic) case where emission tax revenues are not sufficient to fund the public spending requirements, the transfers z_1 and z_2 are zero, so they have no impact on public debt via the third term on the RHS of (2.15). If tax revenues exceed the spending requirements, optimal transfers will turn out to be positive, but only the sum $z_1 + z_2$ will be determined by the optimality conditions. Since we introduced the transfers only to redistribute excessive tax revenues, it is natural to assume $z_1 = z_2$ in the case with positive transfers in order to abstract from further effects on public debt.

From (2.7) we obtain $\lambda_1 = \lambda_2 =: \lambda$. Using this in (2.8) and (2.9) yields

$$\lambda = \frac{X(\tau_1) + \Big\{D_1'[X(\tau_1)] + \gamma D_2'[X(\tau_2) + \gamma X(\tau_1)]\Big\}X'(\tau_1)}{X(\tau_1) + \tau_1 X'(\tau_1)}, \tag{2.17}$$

$$\lambda = \frac{X(\tau_2) + D_2'[X(\tau_2) + \gamma X(\tau_1)]X'(\tau_2)}{X(\tau_2) + \tau_2 X'(\tau_2)}, \tag{2.18}$$

Since $\lambda \geq 1 > 0$ from the slackness conditions (2.12) and (2.13), the respective nominator and denominator on the RHS of (2.17) and (2.18) must have the same sign. They may be either both positive or both negative, in each of these equations. The implications, however, depend on whether the slackness conditions are binding or not. As a benchmark, we start with the case where consumption does not cause environmental damages and obtain the following result, which is proven in Appendix 2.6.2.

Proposition 2.1 *If $D_1 \equiv D_2 \equiv 0$, then the optimal policy is characterized by $z_1 = z_2 = 0$, $\tau_1 = \tau_2 = \tau$ and $b = (g_1 - g_2)/2$, where τ is implicitly determined by $\tau X(\tau) = (g_1 + g_2)/2$ and lies on the increasing side of the Laffer curve $R(\tau)$.*

Proposition 2.1 replicates the results from the previous tax-smoothing literature: If good X does not cause externalities, the only purpose of taxation is to meet the spending requirements. Since taxation is distortionary, the government chooses tax rates that minimize the excess burden. The minimum is reached when the tax rates and, thus, tax revenues are constant over time ($\tau_1 X(\tau_1) = \tau_2 X(\tau_2)$). Due to the excess burden of taxation, the government will not generate more revenues than required for exogenous spending, so transfers are zero in both periods ($z_1 = z_2 = 0$). As a result, equation (2.15) reduces to $b = (g_1 - g_2)/2$, i.e., public debt or savings will only occur if the exogenous spending requirements are non-constant over time. More precisely, a strictly positive level of debt [savings] is optimal if spending is larger [lower] in period 1 than in period 2.

Having established the classical tax-smoothing benchmark, we can now turn to the case with externalities. Due to (2.17) and (2.18), for $D_1, D_2 \neq 0$ there are two important differences to the case without externalities. First, λ may be equal to one such that the slackness conditions are not binding and, second, tax rates may be on the decreasing side of the Laffer curve. To ease exposition, in the subsequent analysis we always assume both tax rates are on the same side of the Laffer curve.[7]

[7] From the intuition behind these results, which we intensively discuss below Proposition 2.2, it should become immediately obvious what happens if both tax rates are on different sides of the Laffer curve.

Starting with the binding case, we obtain the following proposition that is proven in Appendix 2.6.3.

Proposition 2.2 *If $D_1, D_2 \neq 0$ and $\lambda > 1$, the optimal policy is characterized by*
(i) $z_1 = z_2 = 0$.
(ii) $\tau_1 \gtreqqless \tau_2$ if and only if $D_1' + \gamma D_2' \gtreqqless D_2'$.
(iii) If $D_1' + \gamma D_2' < -x_1/X_1'$ and $D_2' < -x_2/X_2'$, then τ_1 and τ_2 are both on the increasing side of the Laffer curve and $\tau_1 > D_1' + \gamma D_2'$ and $\tau_2 > D_2'$. Moreover,

$$b \gtreqqless \frac{g_1 - g_2}{2} \quad \Leftrightarrow \quad D_1' + \gamma D_2' \lesseqqgtr D_2'.$$

(iv) If $D_1' + \gamma D_2' > -x_1/X_1'$ and $D_2' > -x_2/X_2'$, then τ_1 and τ_2 are both on the decreasing side of the Laffer curve and $\tau_1 < D_1' + \gamma D_2'$ and $\tau_2 < D_2'$. Moreover,

$$b \gtreqqless \frac{g_1 - g_2}{2} \quad \Leftrightarrow \quad D_1' + \gamma D_2' \gtreqqless D_2'.$$

Let us first take a look at the optimal tax-transfer policy characterized in parts (i) and (ii) of Proposition 2.2. In order to understand these results, notice that $D_1'+\gamma D_2'$ and D_2' reflect the Pigouvian levels of emission taxation, i.e., the cumulative marginal environmental damages that one unit of emissions from first-period consumption and second-period consumption, respectively, causes over its whole lifetime in the atmosphere. If the slackness conditions are binding ($\lambda > 1$), then taxing good X according to these Pigouvian levels would not generate enough tax revenues to satisfy the spending requirements. Hence, if the tax rates are on the increasing [decreasing] side of the Laffer curve, the government has to set them above [below] the Pigouvian levels in order to generate more tax revenues and to meet the spending requirements (formally, this property is contained in part (iii) [part (iv)] of Proposition 2.2). As shown in part (i) of Proposition 2.2, transfers z_1 and z_2 are not needed in this case since there are no excess tax revenues from Pigouvian internalization of the environmental externalities. Nevertheless, according to part (ii) of Proposition 2.2, optimal tax rates are positively correlated with the cumulative marginal damages in the sense that the tax rate is always higher in the period in which consumption of good X is associated with larger cumulative marginal damages, even though tax rates deviate from their Pigouvian level and are thus not equal to the cumulative marginal damages.

The consequences of this emission tax policy for optimal public debt is characterized in parts (iii) and (iv) of Proposition 2.2. The basic insight from these results is that the presence of environmental externalities can influence the optimal debt level as b may deviate from $(g_1 - g_2)/2$, which is the optimal debt level under tax smoothing in the absence of externalities. To illustrate this, first consider the case where cumulative marginal damages are larger in the first than in the second period ($D_1' + \gamma D_2' > D_2'$), so the optimal tax rate is higher in period 1 than in period 2 ($\tau_1 > \tau_2$) according to part (ii) of Proposition 2.2. This situation is displayed in Figure 2.1.

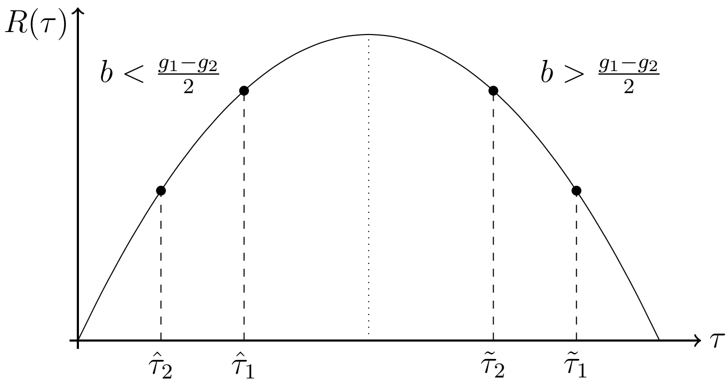

Figure 2.1: The Laffer curve and optimal public debt

If the cumulative marginal damages are relatively low ($D_1' + \gamma D_2' < -x_1/X_1'$ and $D_2' < -x_2/X_2'$), we obtain part (iii) of Proposition 2.2 and optimal tax rates like $(\hat{\tau}_1, \hat{\tau}_2)$ on the increasing side of the Laffer curve. Tax revenues are then larger in period 1 than in period 2, implying a negative effect on the optimal level of debt, i.e., b falls short of the tax-smoothing level $(g_1 - g_2)/2$. In contrast, if the cumulative marginal damages are relatively high ($D_1' + \gamma D_2' > -x_1/X_1'$ and $D_2' > -x_2/X_2'$), part (iv) of Proposition 2.2 holds and the optimal tax rates are represented by $(\tilde{\tau}_1, \tilde{\tau}_2)$ on the decreasing side of the Laffer curve. Tax revenues are then larger in period 2 than in period 1 and we obtain a positive effect on the optimal level of debt, i.e., b is above the tax-smoothing level $(g_1 - g_2)/2$. Not displayed in Figure 2.1 is the case where the cumulative marginal damages are smaller in the first than in the second period ($D_1' + \gamma D_2' < D_2'$). Accordingly to part (ii) of Proposition 2.2, the optimal tax rate is then larger in period 2 than in period 1 and all the results illustrated in Figure 2.1 are reversed.

To sum up, the impact of environmental externalities on optimal public debt depends on the time path of cumulative marginal damages, on the one hand, and the tax rates' location on the Laffer curve, on the other hand. We obtain four cases with different implications for optimal public debt. In order to illustrate that for each of these four cases there is a non-empty set of parameter constellations satisfying the conditions of the respective case, we present a numerical example with a linear-quadratic specification of our model. The utility function for good X in period t is given by $V(x_t) = (1+\alpha)x_t - \beta x_t^2/2$ with $\alpha, \beta > 0$. The damage function in period 1 and 2 reads $D_1(x_1) = \delta_1 x_1$ and $D_2(x_2 + \gamma x_1) = \delta_2(x_2 + \gamma x_1)$, respectively, with $\delta_1, \delta_2 > 0$. The household's first-order condition (2.3) then yields the demand function $X(\tau_t) = (\alpha - \tau_t)/\beta$. The Laffer curve in period t is $R(\tau_t) = (\alpha\tau_t - \tau_t^2)/\beta$ with a maximum at $\tau_t = \alpha/2$ and zero tax revenues at $\tau_t = 0$ and $\tau_t = \alpha$. In the following, we present only numerical examples in which the optimal tax rates are between 0 and α. This ensures positive consumption levels and tax revenues in both periods. The second-order conditions for a welfare maximum are always satisfied under the linear-quadratic specification. Details on this and the numerical examples displayed in Table 2.2 are relegated to Appendix 2.6.4. Note that in all these examples the slackness conditions are binding (since $\lambda > 1$) and the tax-smoothing level of debt would be zero (since $g_1 = g_2$). In the first two examples, optimal tax rates are below $\alpha/2$ and, therefore, on the increasing side of the Laffer curve.

Table 2.2: Numerical examples for optimal emission tax and debt policies

Parameter values							Optimal Policy				Side of Laffer	Marg. damages
α	β	γ	δ_1	δ_2	g_1	g_2	τ_1	τ_2	b	λ	curve: $\tau_t \gtreqless \alpha/2$	$\delta_1 + \gamma\delta_2 \gtreqless \delta_2$
5.0	1.0	1.0	0.1	0.1	1.0	1.0	0.26	0.16	-0.22	1.01	increasing	decreasing
5.0	1.0	0.1	0.1	0.2	1.0	1.0	0.17	0.25	0.18	1.01	increasing	increasing
1.0	1.0	0.1	0.9	0.9	0.2	0.2	0.75	0.70	0.01	1.50	decreasing	decreasing
1.0	1.0	0.1	0.7	0.9	0.2	0.2	0.69	0.76	-0.02	1.28	decreasing	increasing

In the first [second] example, cumulative marginal damages are decreasing [increasing], since $\delta_1 + \gamma\delta_2$ is larger [smaller] than δ_2, implying that it is welfare maximizing to issue a negative [positive] level of debt. The third and fourth example may be interpreted analogously. Hence, the numerical exercise in Table 2 provides examples for each of the four cases in Proposition 2.2.

Finally, we briefly turn to the scenario where the slackness conditions are non-binding ($\lambda = 1$) and tax revenues from Pigouvian internalization of the externality are already sufficient to meet the government's spending requirements. While this scenario seems to be less likely in practice, it is useful from a theoretical point of view since the basic insights from Proposition 2.2 will turn out to generalize to the non-binding case. Appendix 2.6.5 proves

Proposition 2.3 *If $D_1, D_2 \neq 0$ and $\lambda = 1$, the optimal policy is characterized by*

(i) $z_1 = z_2 = \dfrac{(D_1' + \gamma D_2') \cdot X(D_1' + \gamma D_2') + D_2' \cdot X(D_2')}{2} - \dfrac{g_1 + g_2}{2} > 0.$

(ii) $\tau_1 = D_1' + \gamma D_2' \gtreqqless D_2' = \tau_2$ *if and only if* $D_1' + \gamma D_2' \gtreqqless D_2'$.

(iii) *If $D_1' + \gamma D_2' < -x_1/X_1'$ and $D_2' < -x_2/X_2'$, then τ_1 and τ_2 are both on the increasing side of the Laffer curve. Moreover*

$$b \gtreqqless \frac{g_1 - g_2}{2} \quad \Leftrightarrow \quad D_1' + \gamma D_2' \lesseqqgtr D_2'.$$

(iv) *If $D_1' + \gamma D_2' > -x_1/X_1'$ and $D_2' > -x_2/X_2'$, then τ_1 and τ_2 are both on the decreasing side of the Laffer curve. Moreover*

$$b \gtreqqless \frac{g_1 - g_2}{2} \quad \Leftrightarrow \quad D_1' + \gamma D_2' \gtreqqless D_2'.$$

As becomes obvious from parts (iii) and (iv) of Proposition 2.3, with respect to the optimal debt level we obtain qualitatively the same results as in Proposition 2.2: Depending on whether the optimal tax rates are on the increasing or decreasing margin of the Laffer curve and depending on the relation of the cumulative marginal damages in the two periods, introducing externalities into the tax-smoothing analysis may increase or decrease the optimal debt level. The difference to Proposition 2.2 is that the optimal tax rates are now at their Pigouvian levels (equal to the cumulative marginal damages) and that transfers are positive. The reason is that Pigouvian internalization of the externality requires taxes that are high enough to overfulfill the spending requirements. Hence, positive transfers amount to the difference between tax revenues and the exogenous spending requirement.[8]

2.4 Adaptation to Climate Change

So far, we assumed that the government's expenditures g_1 and g_2 were exogenously given and unproductive. In this section, we extend our basic model and take into account the option to invest in an adaptation technology today that reduces the future welfare loss from pollution damages. Formally, we suppose that the government has the opportunity to invest a in period 1, funding the adaptation technology $T(a)$ in period 2 with positive but decreasing returns, i.e., $T'(a) > 0$ and $T''(a) < 0$.

[8] As for the binding case, it is straightforward to identify numerical examples for each of the four cases contained in Proposition 2.3. In fact, we obtain such examples, if in Table 2 we simply replace $g_1 = g_2 = 1$ by $g_1 = g_2 = 0.1$ in the first two rows and $g_1 = g_2 = 0.2$ by $g_1 = g_2 = 0.02$ in the last two rows. Details on these numerical examples can be obtained upon request.

In order to reduce the number of possible cases, we assume in this section that the slackness conditions are binding and the revenues from Pigouvian internalization are not yet enough to finance public expenditures ($z_1 = z_2 = 0$). Moreover, we focus on the case with constant exogenous spending requirements ($g_1 = g_2 = g$) where the canonical tax-smoothing framework prescribes a balanced budget. In (2.5), the first-period budget constraint therefore changes to $\tau_1 X_1(\tau_1) + b = g + a$, while the second-period budget constraint now reads $\tau_2 X_2(\tau_2) - b = g$. Marginal damages in period 1 are still equal to $D_1(x_1)$, while marginal damages in period 2 are now given by the damage function $D_2[x_2+\gamma x_1, T(a)]$ with $D_{2,X} := \partial D_2/\partial(x_2+\gamma x_1) > 0$, $D_{2,XX} := \partial^2 D_2/\partial(x_2+\gamma x_1)^2 \geq 0$, $D_{2,T} := \partial D_2/\partial T(a) < 0$, $D_{2,TT} := \partial^2 D_2/\partial T(a)^2 \geq 0$. Hence, investments in period 1 improve the adaptation technology in period 2 which, in turn, reduces second-period damages at non-increasing rates. This setup reflects that adaptation investments often have no instantaneous effect, either because the scale of the project requires some time lag or because adaptation will only become effective when global warming has exceeded a critical level. For instance, $T(a)$ can represent construction of sea defense walls protecting lowlands from rising sea levels.

The government again maximizes the household's welfare subject to the modified public budget constraints specified above and subject to the non-negativity constraint $a \geq 0$. In Appendix 2.6.6, we show that the welfare-maximizing investment level is strictly positive if the adaptation technology satisfies the Inada condition $\lim_{a\to 0} T'(a) = \infty$. In the following, we proceed on the assumption that this condition is satisfied and that the optimal adaptation investment level is $a > 0$. We now examine how a positive investment level affects the deviation of τ_1 and τ_2 from the tax-smoothing principle as well as the effect on optimal public debt b, in comparison to a situation where adaptation is not available. In order to ensure tractability of this analysis, we confine ourselves to the linear-quadratic example already used in the previous section. Thus, demand for the polluting good is still given by $X(\tau_t) = (\alpha - \tau_t)/\beta$ while the Laffer curve equals $R(\tau_t) = (\alpha\tau_t - \tau_t^2)/\beta$. Taking adaptation into account, the damage functions are now specified as $D_1(x_1) = \delta_1 x_1$ and $D_2\big[x_2 + \gamma x_1, T(a)\big] = \delta_2\big[x_2 + \gamma x_1 - \sqrt{a}\big]$, i.e., the adaptation technology is $T(a) = \sqrt{a}$. Notice that, for this specification, we obtain the optimal policy in the absence of adaptation as a special case, if in the first-order conditions of the welfare maximum we ignore the optimality condition for a and set $a = 0$ in the remaining optimality conditions. Hence, the impact of adaptation a on the optimal policy (τ_1, τ_2, b) can be determined by running a comparative static analysis of the welfare maximum with respect to a and letting a increase from 0 (adaptation not available) to a strictly positive value $a > 0$ (adaptation available). Details on this analysis can be found in Appendix 2.6.7.

Subtracting the second-period budget $\tau_2 X_2(\tau_2) - b = g$ from the first-period budget $\tau_1 X_1(\tau_1) + b = g + a$ and using $R(\tau_t) = \tau_t X(\tau_t)$, we obtain the central equation

$$b = \frac{a}{2} + \frac{R(\tau_2) - R(\tau_1)}{2}. \tag{2.19}$$

According to (2.19), adaptation exerts a direct increasing effect on optimal debt as public debt is used to distribute the costs of adaptation over both periods in lien with the tax-smoothing principle. In addition, adaptation also influences the optimal tax rates τ_1 and τ_2 such that we observe an indirect effect via changes in the tax revenues, $R(\tau_1)$ and $R(\tau_2)$. Differentiating (2.19), the overall effect is

$$\frac{\mathrm{d}b}{\mathrm{d}a} = \frac{1}{2} + \frac{1}{2}\left[R'(\tau_2)\frac{\mathrm{d}\tau_2}{\mathrm{d}a} - R'(\tau_1)\frac{\mathrm{d}\tau_1}{\mathrm{d}a}\right]. \tag{2.20}$$

Equation (2.20) shows that the effect of adaptation on optimal debt will generally deviate from $1/2$, i.e., from an equal distribution of adaptation costs across both periods. The term in square brackets in (2.20) indicates that optimal debt will additionally be influenced by an unequal change in the tax revenues in each period. For the linear-quadratic specification, we show in Appendix 2.6.7 that the change in period t tax revenues equals

$$\frac{\mathrm{d}R(\tau_t)}{\mathrm{d}a} = \frac{\mathrm{d}\tau_t}{\mathrm{d}a}R'(\tau_t) = \frac{R'(\tau_t)^2}{R'(\tau_1)^2 + R'(\tau_2)^2}. \tag{2.21}$$

Substituting (2.21) into (2.20) yields

$$\frac{\mathrm{d}b}{\mathrm{d}a} = \frac{1}{1 + [R'(\tau_1)/R'(\tau_2)]^2}. \tag{2.22}$$

From this expression we already see that the overall effect of adaptation on optimal debt will always be positive. However, whether the indirect effect via changes in tax revenues amplifies or mitigates the direct effect, i.e., whether the total effect is larger or smaller than $1/2$, depends on the relation between $R'(\tau_1)$ and $R'(\tau_2)$, thus, on the exact location of the optimal tax rates on the Laffer curve. In Appendix 2.6.7 we prove

Proposition 2.4 *Consider a linear-quadratic specification of the model with adaptation, i.e., assume* $V(x_t) = (1+\alpha)x_t - \beta x_t^2/2$, $D_1(x_1) = \delta_1 x_1$ *and* $D_2\big[x_2 + \gamma x_1, T(a)\big] = \delta_2\big[x_2 + \gamma x_1 - \sqrt{a}\big]$ *with* $\alpha, \beta, \delta_1, \delta_2 > 0$. *Optimal adaptation is then strictly positive* ($a > 0$), *and* $\tau_1 \gtreqless \tau_2$ *if and only if* $\delta_1 + \gamma\delta_2 \gtreqless \delta_2$, *as in the version of the model without adaptation. The impact of adaptation on optimal fiscal policy is described by the following statements:*

(i) $\dfrac{\mathrm{d}R(\tau_t)}{\mathrm{d}a} > 0$ *for* $t = 1, 2$.

(ii) If τ_1 *and* τ_2 *are both on the increasing side of the Laffer curve, then*

$$\frac{\mathrm{d}b}{\mathrm{d}a} \begin{cases} \in \left(\frac{1}{2}, 1\right), \\ = \frac{1}{2} \\ \in \left(0, \frac{1}{2}\right), \end{cases} \quad \textit{and} \quad \frac{\mathrm{d}R(\tau_1)}{\mathrm{d}a} - \frac{\mathrm{d}R(\tau_2)}{\mathrm{d}a} \begin{cases} < 0, & \textit{if } \delta_1 + \gamma\delta_2 > \delta_2, \\ = 0, & \textit{if } \delta_1 + \gamma\delta_2 = \delta_2, \\ > 0, & \textit{if } \delta_1 + \gamma\delta_2 < \delta_2. \end{cases}$$

(iii) If τ_1 *and* τ_2 *are both on the decreasing side of the Laffer curve, then*

$$\frac{\mathrm{d}b}{\mathrm{d}a} \begin{cases} \in \left(0, \frac{1}{2}\right), \\ = \frac{1}{2} \\ \in \left(\frac{1}{2}, 1\right), \end{cases} \quad \textit{and} \quad \frac{\mathrm{d}R(\tau_1)}{\mathrm{d}a} - \frac{\mathrm{d}R(\tau_2)}{\mathrm{d}a} \begin{cases} > 0, & \textit{if } \delta_1 + \gamma\delta_2 > \delta_2, \\ = 0, & \textit{if } \delta_1 + \gamma\delta_2 = \delta_2, \\ < 0, & \textit{if } \delta_1 + \gamma\delta_2 < \delta_2. \end{cases}$$

Notice first that the insights from part (ii) of Proposition 2.2 generalize to our model specification with endogenous adaptation. That is, optimal emission tax rates are higher in the period where emissions causes higher cumulative marginal damages ($\tau_1 \gtreqless \tau_2$ if and only if $\delta_1 + \gamma\delta_2 \gtreqless \delta_2$). Since the adaptation technology, $T(a) = \sqrt{a}$, satisfies the Inada condition, optimal adaptation investments are strictly positive ($a > 0$).

The most important insight from Proposition 2.4 regards the impact of adaptation on optimal fiscal policy. In order to finance the additional expenditures for adaptation, the government increases optimal tax revenues in both periods, see $\mathrm{d}R(\tau_t)/\mathrm{d}a > 0$ in part (i) of Proposition 2.4, as well as optimal debt, see $\mathrm{d}b/\mathrm{d}a > 0$ in all cases of parts (ii) and (iii) of Proposition 2.4. Moreover, adaptation reduces the deviation of the optimal tax rates from the tax-smoothing principle, i.e., tax rates (as well as revenues) in the two periods move closer together. This is revealed by the sign of $[\mathrm{d}R(\tau_1)/\mathrm{d}a - \mathrm{d}R(\tau_2)/\mathrm{d}a]$ in parts (ii) and (iii) of Proposition 2.4, which depends on the location of the tax rates on the Laffer curve and the development of the cumulative marginal damages. The sign of this expression also determines whether the direct effect of adaptation on optimal debt is amplified or mitigated by the indirect effect, i.e., whether debt increases by more or less than 1/2.

To provide an example, we focus on one case from parts (ii) and (iii) of Proposition 2.4 and leave the discussion of the other cases to the reader.[9] Suppose optimal tax rates are on the decreasing side of the Laffer curve and cumulative marginal damages are decreasing, so we are in part (iii) of Proposition 2.4 with $\delta_1 + \gamma\delta_2 > \delta_2$. This case is illustrated in Figure 2.2.

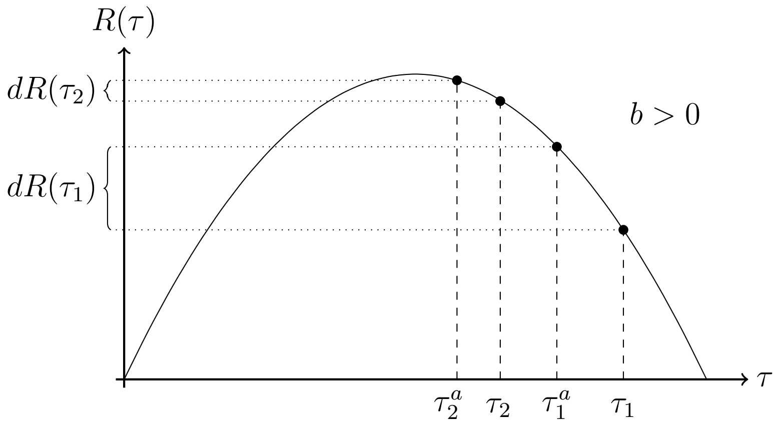

Figure 2.2: Effect of adaptation on tax rates and public debt

Due to $\delta_1 + \gamma\delta_2 > \delta_2$, the government chooses a higher tax rate in the first period than in the second period, $\tau_1 > \tau_2$, and issues a positive level of debt, $b > 0$. The optimal tax rates in the absence of adaptation are simply denoted by τ_1 and τ_2. If adaptation becomes available, the government reduces both tax rates from τ_1 and τ_2 to τ_1^a and τ_2^a, respectively, in order to increase tax revenues in both periods. However, investing in adaptation leads to a more significant drop in the first-period tax rate. This implies a larger gain of tax revenues in period 1, see $\mathrm{d}R(\tau_1)/\mathrm{d}a - \mathrm{d}R(\tau_2)/\mathrm{d}a > 0$ in part (iii) of Proposition 2.4, and the difference in tax revenues, $R(\tau_2) - R(\tau_1)$, falls. The option to invest in adaptation therefore moves optimal taxation closer to the tax-smoothing principle. The intuition is that adaptation reduces second-period environmental damages, so overall, the importance of pollution is reduced and we are closer to a world without externalities. Remember that, nevertheless, optimal public debt increases due to the direct financing effect of adaptation investment. Under the conditions of Figure 2.2, this direct effect is mitigated by the indirect effect, since optimal debt is positive and the difference between first- and second-period tax revenues decreases. Hence, adaptation increases optimal debt by less than 1/2, as shown by $\mathrm{d}b/\mathrm{d}a \in (0, 1/2)$ in part (iii) of Proposition 2.4.

[9] As above, we can provide a numerical example for each of the several cases contained in Proposition 2.4 in order to show that each case is satisfied by a non-empty set of parameter constellations. Details on this numerical exercise can be obtained from the authors upon request.

2.5 Conclusion

In this chapter, we introduce a taxable emissions externality into the standard tax-smoothing framework of public debt. When the government levies an emission tax not only to raise funds for public expenditures but also in order to restrict private consumption of a polluting good, adhering to a balanced budget rule is no longer optimal even if spending requirements are constant over time. Instead, running a deficit at the end of the first period is welfare maximizing either if the tax rates are on the increasing side of the Laffer curve and cumulative marginal damages from pollution increase over time or if the tax rates are on the decreasing side of the Laffer curve while marginal damages decrease over time. In contrast, for constant spending requirements, public savings turn out to be optimal if the tax rates are on the increasing side of the Laffer curve and cumulative marginal damages are decreasing or if the tax rates are on the decreasing side of the Laffer curve and cumulative marginal damages are increasing. In either of these cases, the optimal policy prescribes non-constant tax rates and a non-balanced public budget, deviating from the tax-smoothing principle. In an extension, we introduce adaptation to climate change as an endogenous spending margin. As this technology attenuates environmental damages, we move closer to the tax-smoothing solution with weaker incentives to impose non-constant tax rates. Nevertheless, investments in the adaptation technology always create an additional incentive to increase public debt.

The plenitude of cases for which we derive results raises the question which combination of tax rate locations on the Laffer curve and time paths of cumulative damage is most relevant. In the latter respect, note that many greenhouse gases, especially carbon dioxide, are characterized by exceedingly long atmospheric lifetimes and negligible decay rates (e.g., see Archer et al., 2009). In terms of our formal model, this implies that γ is close to one and cumulative marginal damages are decreasing (i.e., $D_1' + \gamma D_2' \to D_1' + D_2' > D_2'$). However, we have to admit that our stylized approach ignores discounting and this may be crucial for the argument. If future marginal damages are discounted, then our measure of cumulative marginal damages is equal to the concept of the Social Costs of Carbon (SCC) which are usually found to be increasing over time (e.g., see Kornek et al., 2021). It is therefore difficult to judge whether cumulative marginal damages are increasing or decreasing over time. In addition, it is also rather unclear whether optimal emission tax rates are more likely to be located on the increasing or decreasing side of the Laffer curve. Frequently cited, Trabandt and Uhlig (2011) provide empirical evidence suggesting that labor and capital taxes are typically located on the increasing side of the Laffer curve. However, we cannot simply infer that these findings also apply to other kinds of taxes. For instance, in a recent study of the corporate income tax in Canada, Dahlby and Ferede (2018) obtain much less consistent results regarding the location of the tax rates on the Laffer curve. Even more important for our purposes, to the best of our knowledge there is no evidence with regard to the Laffer curve of emission taxes. Intuitively, for relatively large environmental damages, as in the case of climate change, we can not exclude that optimal emission tax rates are on the decreasing side of the Laffer curve.

All these arguments show that an empirical analysis of the cumulative marginal damages and Laffer curves is an important, but also comprehensive task, which is clearly beyond the scope of our theoretical approach. We therefore leave it for future research.

2.6 Appendix

2.6.1 Determinant of the bordered Hessian of (2.7)–(2.11)

The bordered Hessian H of the system of equations (2.7)–(2.11) can be written as

$$H = \begin{pmatrix} L_{\lambda_1\lambda_1} & L_{\lambda_1\lambda_2} & L_{\lambda_1 b} & L_{\lambda_1\tau_1} & L_{\lambda_1\tau_2} \\ L_{\lambda_2\lambda_1} & L_{\lambda_2\lambda_2} & L_{\lambda_2 b} & L_{\lambda_2\tau_1} & L_{\lambda_2\tau_2} \\ L_{b\lambda_1} & L_{b\lambda_2} & L_{bb} & L_{b\tau_1} & L_{b\tau_2} \\ L_{\tau_1\lambda_1} & L_{\tau_1\lambda_2} & L_{\tau_1 b} & L_{\tau_1\tau_1} & L_{\tau_1\tau_2} \\ L_{\tau_2\lambda_1} & L_{\tau_2\lambda_2} & L_{\tau_2 b} & L_{\tau_2\tau_1} & L_{\tau_2\tau_2} \end{pmatrix}$$

$$= \begin{pmatrix} 0 & 0 & 1 & x_1+\tau_1 X_1' & 0 \\ 0 & 0 & -1 & 0 & x_2+\tau_2 X_2' \\ 1 & -1 & 0 & 0 & 0 \\ x_1+\tau_1 X_1' & 0 & 0 & L_{\tau_1\tau_1} & -\gamma D_2'' X_1' X_2' \\ 0 & x_2+\tau_2 X_2' & 0 & -\gamma D_2'' X_1' X_2' & L_{\tau_2\tau_2} \end{pmatrix}, \tag{2.23}$$

with

$$L_{\tau_1\tau_1} = -X_1' - (D_1' + \gamma D_2')X_1'' - (D_1'' + \gamma^2 D_2'')X_1'^2 + \lambda_1(2X_1' + \tau_1 X_1''), \tag{2.24}$$

$$L_{\tau_2\tau_2} = -X_2' - D_2' X_2'' - D_2'' X_2'^2 + \lambda_2(2X_2' + \tau_2 X_2''), \tag{2.25}$$

and $x_t = X(\tau_t)$,$X'_t := X'(\tau_t)$, $X''_t := X''(\tau_t)$, $D'_t := D'(x_t)$ and $D''_t := D''(x_t)$. Calculating the determinant of H with standard methods gives

$$|H| = (x_1 + \tau_1 X'_1)^2 L_{\tau_2\tau_2} + (x_2 + \tau_2 X'_1)^2 L_{\tau_1\tau_1} + 2\gamma(x_1 + \tau_1 X'_1)(x_2 + \tau_2 X'_2) D''_2 X'_1 X'_2. \tag{2.26}$$

2.6.2 Proof of Proposition 2.1

From $D_1 \equiv D_2 \equiv 0$ and (2.17) and (2.18) we obtain

$$\lambda = X(\tau_1)/[X(\tau_1) + \tau_1 X'(\tau_1)], \quad \lambda = X(\tau_2)/[X(\tau_2) + \tau_2 X'(\tau_2)]. \tag{2.27}$$

Since $\lambda \geq 1 > 0$ and $X(\tau_t) > 0$, it follows $X(\tau_t) + \tau_t X'(\tau_t) > 0$ for $t = 1, 2$. Hence, in each period the optimal tax rate is on the increasing side of the Laffer curve. As $X'(\cdot) < 0$, we have $X(\tau_t) + \tau_t X'(\tau_t) < X(\tau_t)$ and therefore (2.27) implies $\lambda > 1$ and $z_1 = z_2 = 0$ by the slackness conditions (2.12) and (2.13). Moreover, (2.27) shows that τ_1 and τ_2 are determined by the same equation implying $\tau_1 = \tau_2 = \tau$. Inserting this into the intertemporal budget constraint (2.14) gives $\tau X(\tau) = (g_1 + g_2)/2$. Finally, substituting $\tau_1 = \tau_2 = \tau$ and $z_1 = z_2 = 0$ into (2.15) yields $b = (g_1 - g_2)/2$.

2.6.3 Proof of Proposition 2.2

Part (i) immediately follows from $\lambda > 1$, (2.12) and (2.13). In order to prove part (ii), rewrite (2.17) and (2.18) as

$$F(\tau_1) = G_1(\tau_1, \tau_2), \quad F(\tau_2) = G_2(\tau_2, \tau_1), \tag{2.28}$$

with

$$F(\tau) := \tau - \frac{1-\lambda}{\lambda}\frac{X(\tau)}{X'(\tau)}, \quad F'(\tau) := 1 - \frac{1-\lambda}{\lambda}\frac{[X'(\tau)]^2 - X(\tau)X''(\tau)}{[X'(\tau)]^2} \gtreqless 0, \tag{2.29}$$

and

$$G_1(\tau_1, \tau_2) := \frac{D'_1[X(\tau_1)] + \gamma D'_2[X(\tau_2) + \gamma X(\tau_1)]}{\lambda},$$
$$\Rightarrow \frac{\partial G_1(\tau_1, \tau_2)}{\partial \tau_1} = \frac{\{D''_1[\cdot] + \gamma^2 D''_2[\cdot]\}\, X'(\tau_1)}{\lambda} \leq 0, \tag{2.30}$$
$$G_2(\tau_2, \tau_1) := \frac{D'_2[X(\tau_2) + \gamma X(\tau_1)]}{\lambda}, \quad \frac{\partial G_2(\tau_2, \tau_1)}{\partial \tau_2} = \frac{D''_2[\cdot] X'(\tau_2)}{\lambda} \leq 0 \tag{2.31}$$

where the signs of $\partial G_1(\tau_1,\tau_2)/\partial\tau_1$ and $\partial G_2(\tau_2,\tau_1)/\partial\tau_2$ follow from $D_t''[\cdot] \geq 0$ and $X'(\tau_t) < 0$. Hence, G_1 and G_2 are non-increasing functions in τ_1 and τ_2, respectively, while $F(\tau)$ may be increasing or decreasing in its only argument τ. Consider first the case where $F(\tau)$ is increasing in τ. This case is illustrated in Figure 2.3.

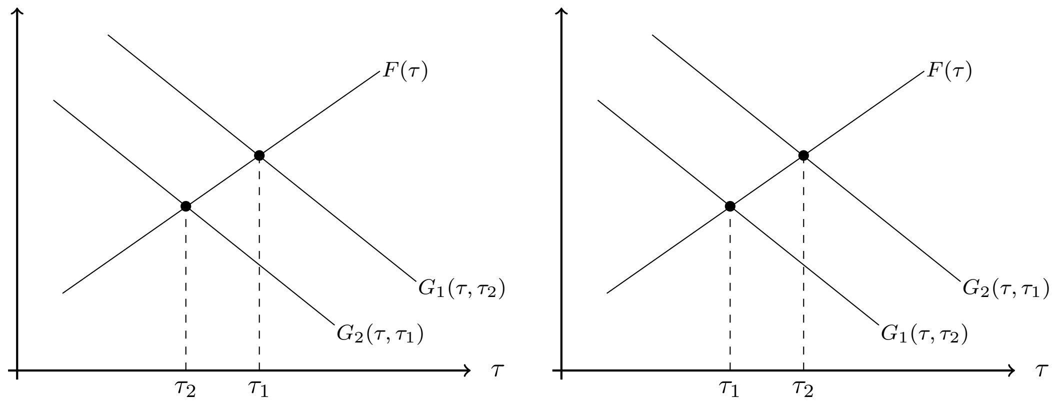

Figure 2.3: Relationship between marginal damages and optimal tax rates

In the left panel of this figure, we consider the case where τ_1 and τ_2 are such that $D_1' + \gamma D_2' > D_2'$ and, thus, $G_1(\tau,\tau_2)$ lies above $G_2(\tau,\tau_1)$. It immediately follows that $\tau_1 > \tau_2$. In the right panel, τ_1 and τ_2 are such that $D_1' + \gamma D_2' < D_2'$ and $G_1(\tau,\tau_2)$ lies below $G_2(\tau,\tau_1)$. Hence, we obtain $\tau_1 < \tau_2$. If τ_1 and τ_2 are such that $D_1' + \gamma D_2' = D_2'$, then $G_1(\tau,\tau_2)$ and $G_2(\tau,\tau_1)$ are identical and we obtain $\tau_1 = \tau_2$ (not displayed in Figure 3). The same line of reasoning applies if the function $F(\tau)$ is decreasing but not steeper than $G_1(\tau,\tau_2)$ and $G_2(\tau,\tau_1)$ (also not displayed in Figure 3). This completes the proof of part (ii). Note that it is not possible that $F(\tau)$ is decreasing and steeper than $G_1(\tau,\tau_2)$ and $G_2(\tau,\tau_1)$. In this case, it can be shown that $L_{\tau_1\tau_1} > 0$ and $L_{\tau_2\tau_2} > 0$ and, thus, the bordered Hessian is $|H| > 0$, i.e., the second-order conditions of welfare maximization are violated.[10]

Next turn to part (iii). If $D_1' + \gamma D_2' < -x_1/X_1'$ and $D_2' < -x_2/X_2'$, (2.17) and (2.18) imply $x_1 + \tau_1 X'(\tau_1) > 0$ and $x_2 + \tau_2 X'(\tau_2) > 0$, i.e., both tax rates are on the increasing side of the Laffer curve. Moreover, rearranging (2.17) and (2.18) in this case gives $\tau_1 > D_1' + \gamma D_2'$ and $\tau_2 > D_2'$. Taking into account part (ii) and that both

[10] We can rewrite (2.25) as $L_{\tau_2\tau_2} = (2\lambda_2 - 1)X_2' - D_2''X_2'^2 - (D_2' - \lambda_2\tau_2)X_2''$. From (2.9) we obtain $D_2' - \lambda_2\tau_2 = (\lambda_2 - 1)X_2/X_2'$. Inserting this expression into the second derivative of the Lagrangian gives $L_{\tau_2\tau_2} = \left[(2\lambda_2 - 1)(X_2')^2 - D_2''X_2'^3 + (1 - \lambda_2)X_2X_2''\right]/X_2'$. If $F(\tau)$ is decreasing and steeper than G_2, it is straightforward to show with the help of (2.29) and (2.31) that the bracketed term in $L_{\tau_2\tau_2}$ is negative and, thus, $L_{\tau_2\tau_2} > 0$. In the same way we can show $L_{\tau_1\tau_1} > 0$ if $F(\tau)$ is decreasing and steeper than G_1. Using theses signs in (2.26) and taking into account that we focus on the case where both tax rates are on the same side of the Laffer curve, i.e., $\text{sign}\{x_1 + \tau_1 X_1'\} = \text{sign}\{x_2 + \tau_2 X_2'\}$, we obtain $|H| > 0$.

tax rates are on the increasing side of the Laffer curve, we obtain $\tau_1 X(\tau_1) \lesseqqgtr \tau_2 X(\tau_2)$ if and only if $D_1' + \gamma D_2' \lesseqqgtr D_2'$. Using this together with $z_1 = z_2 = 0$ in (2.15) proves the result with respect to optimal debt b in part (iii). Finally, the proof of part (iv) is perfectly analogous to that of part (iii).

2.6.4 Details on the numerical examples in Table 2.2

Under the linear-quadratic specification and binding slackness conditions ($z_1 = z_2 = 0$), the intertemporal budget constraint (2.14) becomes

$$\frac{\alpha\tau_1 - \tau_1^2}{\beta} + \frac{\alpha\tau_2 - \tau_2^2}{\beta} = g_1 + g_2. \tag{2.32}$$

The function for optimal debt (2.15) equals

$$b = \frac{g_1 - g_2}{2} + \frac{\alpha\tau_2 - \tau_2^2 - (\alpha\tau_1 - \tau_1^2)}{2\beta}. \tag{2.33}$$

The first-order conditions (2.17) and (2.18) for welfare maximization can be written as

$$\lambda = \frac{\alpha - \tau_1 - \delta_1 - \gamma\delta_2}{\alpha - 2\tau_1}, \quad \lambda = \frac{\alpha - \tau_2 - \delta_2}{\alpha - 2\tau_2}. \tag{2.34}$$

For a given parameter constellation $(\alpha, \beta, \gamma, \delta_1, \delta_2, g_1, g_2)$, we solve the system of equations (2.32)–(2.34) with respect to the optimal policy $(\tau_1, \tau_2, b, \lambda)$ with the help of the software Mathematica. In order to prove the second-order conditions note that from (2.24) and (2.25) we obtain

$$L_{\tau_1\tau_1} = L_{\tau_2\tau_2} = \frac{1 - 2\lambda}{\beta} < 0 \tag{2.35}$$

since $\lambda > 1$. The determinant of the bordered Hessian (2.26) turns into

$$|H| = \frac{1 - 2\lambda}{\beta^3}\left[(\alpha - 2\tau_2)^2 + (\alpha - 2\tau_1)^2\right] < 0. \tag{2.36}$$

Hence, under the linear-quadratic specification of our model, the second-order conditions of welfare maximization are always satisfied.

2.6.5 Proof of Proposition 2.3

For $\lambda = 1$ equation (2.17) and (2.18) can be written as

$$\frac{x_1 + (D_1' + \gamma D_2') \cdot X_1'}{x_1 + \tau_1 X_1'} = 1 = \frac{x_2 + D_2' \cdot X_2'}{x_2 + \tau_2 X_2'}, \tag{2.37}$$

It follows that the optimal tax rates are $\tau_1 = D_1' + \gamma D_2'$ and $\tau_2 = D_2'$ which proves part (ii) of Proposition 2.3. For $D_1' + \gamma D_2' < -x_1/X_1'$ and $D_2' < -x_2/X_2'$, equation (2.37) implies that τ_1 and τ_2 are on the increasing side of the Laffer curve. As we assume $z_1 = z_2$, the optimal debt level in (2.15) becomes

$$b = \frac{g_1 - g_2}{2} + \frac{D_2' \cdot X(D_2') - (D_1' + \gamma D_2') \cdot X(D_1' + \gamma D_2')}{2}. \tag{2.38}$$

Since the tax rates are on the increasing side of the Laffer curve, we immediately obtain the result for b in part (iii), which completes the proof of part (iii). The proof of part (iv) is analogous. Finally, inserting (2.38) into (2.10) and (2.11) and solving with respect to z_1 and z_2 shows part (i) of Proposition 2.3.

2.6.6 Proof of an interior solution with respect to welfare-maximizing adaptation

The Lagrangian for the modified welfare-maximization problem in the presence of adaptation reads

$$\begin{aligned} L = \sum_{t=1,2} \Big\{ V\big[X(\tau_t)\big] + 1 - (1 + \tau_t) X(\tau_t) \Big\} \\ - D_1\big[X(\tau_1)\big] - D_2\big[X(\tau_2) + \gamma X(\tau_1), T(a)\big] \\ + \lambda_1\big[\tau_1 X(\tau_1) + b - g - a\big] + \lambda_2\big[\tau_2 X(\tau_2) - b - g\big]. \end{aligned} \tag{2.39}$$

We obtain the first-order conditions

$$L_b = \lambda_1 - \lambda_2 = 0, \tag{2.40}$$

$$L_{\tau_1} = -X(\tau_1) - \Big\{D_{1,X}[X(\tau_1)] + \gamma D_{2,X}[X(\tau_2) + \gamma X(\tau_1), T(a)]\Big\}X'(\tau_1) + \lambda_1\Big[X(\tau_1) + \tau_1 X'(\tau_1)\Big] = 0, \tag{2.41}$$

$$L_{\tau_2} = -X(\tau_2) - D_{2,X}[X(\tau_2) + \gamma X(\tau_1), T(a)]X'(\tau_2) + \lambda_2\Big[X(\tau_2) + \tau_2 X'(\tau_2)\Big] = 0, \tag{2.42}$$

$$L_{\lambda_1} = \tau_1 X(\tau_1) + b - g - a = 0, \tag{2.43}$$

$$L_{\lambda_2} = \tau_2 X(\tau_2) - b - g = 0, \tag{2.44}$$

as well as the slackness conditions for adaptation investments

$$L_a = -D_{2,T}[X(\tau_2) + \gamma X(\tau_1), T(a)]T'(a) - \lambda \leq 0, \quad a \geq 0, \quad aL_a = 0. \tag{2.45}$$

As long as the adaptation technology satisfies the Inada condition $\lim_{a\to 0} T'(a) = \infty$, the latter condition implies $a > 0$, since for $a \to 0$ we have $L_a \to \infty > 0$ and $L_a \leq 0$ is violated.

2.6.7 Proof or Equation (2.21) and Proposition 2.4

In order to derive the marginal effect of adaptation on the tax rates used in (2.21), note that we can view (2.40)–(2.44) as a system of five equations that determine the five variables $(b, \tau_1, \tau_2, \lambda_1, \lambda_2)$ as functions of a. Due to the linear-quadratic specification of the model, we obtain $D_{1,X} + \gamma D_{2,X} = \delta_1 + \gamma\delta_2$ and $D_{2,X} = \delta_2$. Hence, adaptation a influences $(b, \tau_1, \tau_2, \lambda_1, \lambda_2)$ only via equation (2.43). We employ Cramer's Rule to obtain

$$\frac{\mathrm{d}\tau_t}{\mathrm{d}a} = \frac{|J_{\tau_t}|}{|J|}, \tag{2.46}$$

where J represents the Jacobian of (2.40)–(2.44) and J_{τ_t} denotes the adjusted Jacobian in which the column containing the derivatives with respect to τ_t is substituted for by the replacement vector of a containing the derivatives with respect to a. The Jacobian J coincides with the bordered Hessian in (2.23). Hence, in the linear-quadratic example, we obtain

$$
\begin{aligned}
|J| = |H| = &\begin{vmatrix} 0 & 0 & 1 & R'(\tau_1) & 0 \\ 0 & 0 & -1 & 0 & R'(\tau_2) \\ 1 & -1 & 0 & 0 & 0 \\ R'(\tau_1) & 0 & 0 & (1-2\lambda)/\beta & 0 \\ 0 & R'(\tau_2) & 0 & 0 & (1-2\lambda)/\beta \end{vmatrix} \\
= &\frac{1-2\lambda}{\beta}\left[R'(\tau_1)^2 + R'(\tau_2)^2\right] < 0,
\end{aligned}
\tag{2.47}
$$

where we use $\lambda_1 = \lambda_2 = \lambda > 1$ and $R'(\tau_t) = x_t + \tau_t X'(\tau_t) X(\tau)$. In order to obtain J_{τ_1} $[J_{\tau_2}]$, we substitute the replacement vector $(-L_{\lambda_1 a}, -L_{\lambda_2 a}, -L_{ba}, -L_{\tau_1 a}, -L_{\tau_2 a})' = (1, 0, 0, 0, 0)'$ for the fourth [fifth] column in the determinant of (2.47). The adjusted Jacobian can then be computed as

$$
|J_{\tau_t}| = \frac{1-2\lambda}{\beta} R'(\tau_t). \tag{2.48}
$$

Dividing (2.48) by (2.47) results in

$$
\frac{\mathrm{d}\tau_t}{\mathrm{d}a} = \frac{R'(\tau_t)}{R'(\tau_1)^2 + R'(\tau_2)^2}. \tag{2.49}
$$

which completes the proof of equation (2.21).

In order to proof Proposition 2.4, first, note that we can show $\tau_1 \gtreqless \tau_2$ if and only if $\delta_1 + \gamma\delta_2 \gtreqless \delta_2$ by the same steps as in Proposition 2.2 since for this proof we only need equations (2.41) and (2.42) which do not depend on a under the linear-quadratic model specification. To proof part (i) of Proposition 2.4 simply verify that (2.21) is always positive. Next, consider part (ii) of 2.4 and focus on the case $\delta_1 + \gamma\delta_2 > \delta_2$ such that $\tau_1 > \tau_2$. Since both tax rates are on the increasing side of the Laffer curve in this case, $R''(\tau_t) = -2/\beta < 0$ implies $R'(\tau_1) < R'(\tau_2)$. Hence, the effect in (2.49), while positive in both periods, is larger on τ_2 than on τ_1. Since τ_2 was initially lower than τ_1 in the absence of adaptation, this implies that the wedge between the tax rates decreases. The same holds true with respect to the changes of tax revenues captured by (2.21), so we obtain $\mathrm{d}R(\tau_1)/\mathrm{d}a - \mathrm{d}R(\tau_2)/\mathrm{d}a < 0$. The effect of a on public debt in (2.22) is $\mathrm{d}b/\mathrm{d}a \in (1/2, 1)$ since $R'(\tau_1)/R'(\tau_2) < 1$ due to $R'(\tau_2) > R'(\tau_1) > 0$. In the opposite case, if $\delta_1 + \gamma\delta_2 < \delta_2$, we observe that $\tau_1 < \tau_2$. Then, $R'(\tau_1) > R'(\tau_2) > 0$ implies that $\mathrm{d}\tau_1/\mathrm{d}a > \mathrm{d}\tau_2/\mathrm{d}a$, $\mathrm{d}R(\tau_1)/\mathrm{d}a - \mathrm{d}R(\tau_2)/\mathrm{d}a > 0$ and $\mathrm{d}b/\mathrm{d}a \in (0, 1/2)$. Finally, for constant marginal damages $\delta_1 + \gamma\delta_2 = \delta_2$, we have

$\tau_1 = \tau_2$ and, thus, $R'(\tau_1) = R'(\tau_2)$, $\mathrm{d}\tau_1/\mathrm{d}a = \mathrm{d}\tau_2/\mathrm{d}a$, $\mathrm{d}R(\tau_1)/\mathrm{d}a - \mathrm{d}R(\tau_2)/\mathrm{d}a = 0$ and $\mathrm{d}b/\mathrm{d}a = 1/2$, which completes the proof of part (ii) of Proposition 2.4. The proof of part (iii) can be conducted analogously if we recall that on the decreasing side of the Laffer curve $R'(\tau_t) < 0$, which means that (2.49) is negative. Therefore, both tax rates decrease in response to a marginal increase in a.

2.6.8 Additional income tax with collection cost

Suppose that in addition to the emission tax rate, τ_t, the government can also levy a tax, S_t, on the household's income $m = 1$. The private budget constraint in period t then reads

$$1 - S_t = y_t + (1 + \tau_t)x_t. \tag{2.50}$$

Hence, the inclusion of S_t leaves the household's decision on optimal consumption of the polluting good unchanged. In period t, we still obtain $x_t = X(\tau_t)$. In order to model the distortionray effect of income taxation, we follow the stylized approach of the underlying tax-smoothing framework in Barro (1979) and assume that the deadweight loss of income taxation is given by the ad-hoc function $C(S_t)$ with $C', C'' > 0$. This function may reflect, for example, the excess burden or collection costs of income taxation.

It is sensible to focus on the case where the revenues from Pigouvian taxation alone are not sufficient to fund the exogenous public spending requirements as assumed in Proposition 2.2. Hence, the Lagragian to the government's welfare maximization problem equals

$$\begin{aligned} L = \sum_{t=1}^{2} \Big\{ 1 - S_t - (1+\tau_t)X(\tau_t) + V\big[X(\tau_t)\big] \Big\} - D\big[X(\tau_1)\big] \\ + \lambda_1 \big[S_1 + \tau_1 X(\tau_1) + b - g_1\big] + \lambda_2 \big[S_2 + \tau_2 X(\tau_2) - b - g_2\big] \\ - D\big[X(\tau_2) + \gamma X(\tau_1)\big] - C(S_1) - C(S_2). \end{aligned} \tag{2.51}$$

where the revenues from income taxation appear in the public budget constraints. It is straightforward to show that the first-order conditions with respect to τ_1, τ_2 and b are identical to the model without income taxation. Thus, the proof of Proposition 2.2 extends to the updated problem and still implies $\tau_1 \gtreqless \tau_2$ if $D_1' + \gamma D_2' \gtreqless D_2'$, as in the model without income taxation.

The first-order conditions with respect to the Lagrangian multipliers now read

$$L_{\lambda_1} = S_1 + \tau_1 X(\tau_1) + b - g_1 = 0, \tag{2.52}$$

$$L_{\lambda_2} = S_2 + \tau_2 X(\tau_2) - b - g_2 = 0, \tag{2.53}$$

whereas the first-order conditions for the optimal income taxes are

$$L_{S_1} = -1 + \lambda_1 - C'(S_1) = 0, \tag{2.54}$$

$$L_{S_2} = -1 + \lambda_2 - C'(S_2) = 0 \tag{2.55}$$

Since $L_b = 0$ implies $\lambda_1 = \lambda_2$, we obtain

$$C'(S_1) = C'(S_2) \quad \Rightarrow \quad S_1 = S_2. \tag{2.56}$$

Moreover, (2.52) and (2.53) together with $S_1 = S_2$ result in

$$\begin{aligned} b &= \frac{g_1 - g_2}{2} + \frac{\tau_2 X(\tau_2) - \tau_1 X(\tau_1)}{2} + \frac{S_2 - S_1}{2} \\ &= \frac{g_1 - g_2}{2} + \frac{\tau_2 X(\tau_2) - \tau_1 X(\tau_1)}{2} \end{aligned} \tag{2.57}$$

which is also exactly the same as in the model without income taxation. As a result, the central findings of this chapter also occur in a model with an additional tax on income.

Chapter 3

Emissions and Strategic Debt under Reelection Uncertainty

3.1 Introduction[11]

The political economy of public debt has received considerable attention in the previous literature as sovereign debt creates a link between current and future political decisions, even if today's government will not remain in office. The reasons why current political decision makers would want to embrace public debt as a strategic instrument are manifold and range from the aim of minimizing the pork barrel's contribution to debt stabilization (Alesina and Drazen, 1991) over concerns regarding interregional or intergenerational redistribution (see Cukierman and Meltzer, 1989 or Weingast et al., 1981) to binding future governments' allocation of public funds.[12] Likewise, the political economy of environmental policy has been examined at least since Buchanan and Tullock (1975), who show why incumbent firms in a polluting industry would prefer the introduction of quotas over an emission tax. The subsequent theoretical literature has put its primary emphasis on analyzing how interest groups can influence environmental policy through lobbying (see Aidt, 1998 and Oates and Portney, 2003 for an overview). However, to the best of my knowledge, a combined approach which intertwines the political economy of public debt and environmental policy has yet to be established.

This chapter aims at filling this gap and contributes to the integrated political economy analysis of fiscal and climate policy by introducing stock pollutants

[11] The contents of this chapter are based on M. Kellner (2021) 'Environmental Pollution and the Political Economy of Public Debt' which was previously made available as an *SSRN working paper*.

[12] Alesina and Passalacqua (2016) provide a recent survey of the existing literature on the political economy of public debt.

in a political economy model of public debt with uncertain reelection. Within this framework, I show that strategic incentives are influenced not only by an intertemporal *budget* interaction but also an intertemporal *emission* interaction which implies three main results. First, reelection uncertainty always reduces pollution in the first period in comparison to the outcome under certain reelection if emissions are relatively persistent. This result occurs even if the first-period government ignores environmental damages, because inheriting a large stock of pollution from the previous government distorts second-period decisions. Second, while voting still leads to a strategic increase in public debt like in the underlying model without pollution, this effect is no longer necessarily detrimental but can lead to efficiency gains as, in the presence of sufficiently persistent stock pollution, there are normative reasons to deviate from a balanced budget and issue public debt. Third, intertemporal welfare may improve as a result of reelection uncertainty, when an environmentally unaware incumbent competes against a green party. In this case, more efficient emission abatement in both periods can add to the welfare gain from the budget interaction if higher public debt is indeed efficient, or outweigh the welfare loss if strategic debt accumulation is detrimental. In both cases, the certain reelection outcome would only be third-best, whereas voting with reelection uncertainty leads to a second-best solution and, thus, is preferable from a welfare-maximizing perspective.

To derive these findings, I employ a two-period model where the first-period government faces uncertainty about reelection in the second period and allocates funds between two public goods. While provision of one good is clean (e.g., R&D subsidies to clean industries, spending on education or health services), provision of the other good creates emissions (e.g., road infrastructure or tax credits to polluting industries) and, thus, adds to a stock of environmental pollution. The parties running for office in each period disagree on how much of the pollution externality should be internalized. I assume that politicians are either 'environmentalists' (E) who internalize (most or all) pollution damages or 'industrialists' (I) who appreciate the externality only partially (or not at all) in their objective function. This setup can be motivated, for instance, by the recent change to the computation of the social cost of carbon (SCC) in the US. Under the Clean Air Act, as adhered to by the Obama administration, the SCC measured the global costs of carbon emission. Under the Trump administration, only 'domestic' benefits from avoided climate change were taken into account which considerably reduced the part of the SCC taken into account (EPA, 2017). While the Biden administration's stance on measuring the SCC is yet unclear, rejoining the Paris Climate Accord indicates that the current US government is more likely to account for global emission damages than its predecessor. These observations provide an illustrative example of how internalization preferences can vary in a bipartisan voting economy.

Public debt is no longer the only channel through which the incumbent government can influence future policy making. As in the underlying political economy models of public debt without pollution, first-period borrowing serves as a strategic measure to confine future governments' spending capabilities and shift funds to the first period, where the incumbent government can still allocate the public budget to its own liking. However, due to the stock accumulation of pollution, first-period emissions cause damages in both periods creating a second channel through which the incumbent influences future decision making. To illustrate how this affects strategic incentives, suppose party I is initially in office but will be superseded by E in the second period. Since I prefers a higher provision of the polluting good than E will provide in the second period, the incumbent wants to accumulate debt and spend even more on the polluting good in the first period. Yet, since emissions remain in the atmosphere and decay slowly in my model, party E would not just dispose of a smaller budget but also inherit a larger stock of emissions from the first period which leads to even lower spending on the polluting good in the second period. Therefore, the emission interaction disciplines the incumbent I to pollute less in the first period if emissions are sufficiently persistent. In the opposite case, where party E holds office in the first period but expects to be replaced by I in the second period, E anticipates that too much of the polluting good will be provided in the next period. To prevent pollution damages from spiking in the second period, E cuts first-period spending on the polluting good while running an inefficiently high deficit to restrict second-period provision by party I. As a result, incumbent E will over-provide the clean public good. Hence, I obtain my first result that voting with uncertain reelection induces both parties to abate more emissions in the first period when compared to their policies under certain reelection.

The second result is closely related to this intuition. Since second-period funds will never be spent optimally from the incumbent's perspective if their competitor wins the elections, any first-period government has an incentive to leave fewer funds for the second period. This strategic debt increase is well known from the previous literature. However, while most contributions identify the strategic incentive to be inefficient, I find that the budget can, in fact, become more efficient when the incumbent government issues debt strategically because stock pollution provides a reason to deviate from a balanced budget in the social optimum. Similar to the effects identified in Chapter 2, this is the case when emissions are more harmful, the later they are released into the atmosphere (i.e., increasing social cost of carbon over time) such that the social planner would spend more on the polluting public good today. Nonetheless, depending on whether it is first-best to issue debt or accumulate savings and contingent on the parameters of the damage function, it is still possible that reelection uncertainty entails a detrimental effect on the public budget.

My third main finding implies that the total intertemporal welfare effect of reelection uncertainty is path dependent, i.e., if party E is initially in office, reelection uncertainty not only affects the budget efficiency but also leads to a higher intertemporal welfare loss from pollution if party I takes office in the second period. In contrast, if I constitutes the first-period government, strategic incentives to pollute less in the first period are joined by a lower provision of the polluting good in the second period such that total pollution damages decrease in comparison to certain reelection of I. If party E demands an excessively high over-internalization, the economy may end up with inefficient under-provision of the polluting good. Otherwise, emission levels become more efficient as a result of voting uncertainty which either reinforces the welfare gain from the budget interaction if strategic debt is welfare-improving, or can attenuate the strategic inefficiency if public debt is excessively high under reelection uncertainty. This implies that there are two channels through which strategic incentives associated with voting uncertainty can improve welfare in comparison to the certain reelection outcome. By committing to stringent climate policy if elected in the second period, a green party may 'force' a conservative incumbent to engage in emission abatement. Furthermore, pure political economy models of public debt can overestimate the strategic debt inefficiency associated with voting which might lead to overzealous efforts to reduce reelection uncertainty in the favor of budget efficiency.

This chapter is closely related to the literature on the political economy of public debt. In particular, I build on and expand the framework established by Tabellini and Alesina (1990) who analyze the effects on public debt when voters decide about the allocation of funds between two public goods. The bipartisan approach with two parties (here, I and E) alternating in office is similar to the models of Persson and Svensson (1989) and Alesina and Tabellini (1990). However, these seminal contributions focus exclusively on strategic debt incentives when the government provides non-durable, clean public goods. By neglecting other interactions, they concur that the public budget should be balanced in the optimum and strategic debt is detrimental to welfare. Peletier et al. (1999) who modify one public good to be a durable investment which earns returns in the future and, recently, Bouton et al. (2020), who introduce entitlements (e.g., future pension payments) as a means to influence future decisions, both show that adhering to a balanced budget rule may be detrimental in the presence of a second interaction. Interestingly, both models reach this conclusion through fundamentally different interactions: productive investments increase future public spending capabilities for all while entitlements redistribute to the current government's supporters. My analysis joins their rank by unveiling yet another interaction with similar implications via damages from stock pollution. In another recent study, Piguillem and Riboni (2021) show that the debt inefficiency observed by the underlying literature can be attenuated when incumbent and opposition party have to agree on relaxing debt rules. This interaction differs from the three above because both parties deliberately engage in a bargaining process. Regarding the strategic effect on emission abatement, Voß (2014) also shows in a working paper that reelection uncertainty can induce the incumbent to pollute less than under certain reelection. However, this analysis does not consider the government's ability to issue debt and, thus, ignores the budget interaction which also affects the impact of voting on welfare in my model.

The remainder of this chapter is organized as follows. The next section outlines the model. In Section 3.3, I derive the social planner's solution as a benchmark next to the outcome if a politician, who does not fully internalize emissions, is reelected with certainty. Section 3.4 provides the central results regarding political economy incentives under reelection uncertainty. The chapter concludes with a critical discussion of my findings and their limitations.

3.2 Model

The model in this chapter is founded on the contribution by Tabellini and Alesina (1990) where public funds have to be allocated between two different public goods, G and F, in a two-period partial equilibrium model. The quantities of goods G and F provided in period $t = 1, 2$ are denoted by g_t and f_t, respectively. The innovation is that the provision of one public good is also associated with environmental pollution. I choose good G as the polluting good and F as the non-polluting good.[13] In period t, pollution is generated at a constant ratio to the provision of g_t and causes damages according to the damage function

$$D_t(\gamma g_{t-1} + g_t), \qquad \text{with} \quad D_t' > 0, \; D_t'' > 0, \tag{3.1}$$

[13] All subsequent findings intuitively also hold in scenarios where both public goods cause pollution, but provision of g_t is more polluting than producing the same quantity of f_t.

such that γ captures the persistence of pollutants. Since I assume that $\gamma \in (0, 1]$, total pollution accumulates as a stock over time. For instance, this stock can represent the atmospheric concentration of greenhouse gas emissions. Hence, damages amount to the detrimental effect of climate change and global warming on welfare. Without loss of generality, pollution from g_0 is normalized to zero. If pollution decays immediately, i.e., $\gamma = 0$, strategic interactions between different decision makers would only arise from the level of public debt but not from the history of public good provision. Pollution then only affects the *intra*-period allocation of funds between g_t and f_t. In this case, the results closely resembles the outcome in the underlying model where politicians have different preference rates for g_t and f_t in the absence of pollution.[14]

I assume a bipartisan model with an environmentalists' party, E, and an industrialists' party, I. For both parties, utility from consuming goods G and F in period t is given by $u(g_t)$ and $u(f_t)$, respectively, with $u' > 0 > u''$. Moreover, party $i = E, I$ takes the share θ_i of the true damage in (3.1) into account. Therefore, the objective function of party i is given by

$$W^i = \mathbb{E}\Big\{ \sum_{t=1}^{2} u(g_t) + u(f_t) - \theta_i D_t(\gamma g_{t-1} + g_t) \Big\}, \tag{3.2}$$

where $\mathbb{E}$ denotes the expectations operator. Future utility is not discounted to avoid confounding debt accumulation due to 'consumption' smoothing with the political economy mechanism underlying strategic debt.

Clearly, θ_i is the only parameter in (3.2) specific to party i. I refer to this as the *pollution awareness* or *internalization preference* parameter of party i. The specification allows for different interpretations. For instance, it may represent the degree to which parties acknowledge that the damage from climate change is driven by man-made emissions.[15] Underestimating θ_i can result from biased voter preferences, lobbying activities, egoistic politicians with vested interests in polluting industries, ideologies or misinformation on the true extent of anthropogenic climate

[14]Unlike Tabellini and Alesina (1990), I assume that, apart from varying internalization preferences, all parties have the same preference for both goods. Thereby, I restrict my attention to strategic incentives arising from the environmental impact of good G. Note that there would be additional strategic interactions affecting the public budget if preference rates vary between parties.

[15]To be precise, this means that the welfare function in (3.2) would also have to include the share of emission damages, $(1 - \theta_i)\overline{D}_t(g_t)$, believed to be a natural constant, where $\overline{D}_t(g_t)$ indicates that these damages are falsely accepted as exogenously given. Thus, this term does not affect the decision problem and is omitted in equation (3.2) for the sake of brevity.

change. Alternatively, as suggested by the EPA-proposal mentioned in the introduction, a local politician may be aware of the full damages from pollution, yet, they are only interested in the share of damages, θ_i, that occurs domestically. Hence, depending on the interpretation of θ_i, it can be rational for local parties to only partially internalize emission damages. In contrast, the social planner aggregates across all jurisdictions and knows the full extent of damages from provision of the polluting good such that $\theta_i = \theta^* = 1$ in the first-best solution. I assume that the pollution awareness parameter is restricted to the interval $\theta_i \in [0, 1]$ and all voters i identify with either party E or I. Therefore, the spectrum of internalization preferences is restricted to no ($\theta_i = 0$), partial ($0 < \theta_i < 1$) or full ($\theta_i = 1$) internalization. Nonetheless, it is also possible that environmental activists or poorly informed voters overestimate the extent of pollution damages. In this case party i may prefer an internalization rate $\theta_i > 1$. Since this preference would most likely describe a fringe party with negligible political leverage, this case is excluded from the main analysis and will only be hinted at whenever results are notably affected. [16]

Turning to the government's decision problem, the economy is endowed with exogenously given public funds normalized to one at the beginning of each period. Assuming that there is no outstanding debt at the beginning of the first period and that public debt, b, matures after on period, the first- and second-period budget constraints are given by, respectively,

$$g_1 + f_1 \leq 1 + b, \tag{3.3a}$$

$$g_2 + f_2 \leq 1 - b. \tag{3.3b}$$

Equations (3.3a) and (3.3b) implicitly bind the second-period government to fully repay public debt inherited from the previous period. Like the private discount rate, the real interest rate is set to zero to ensure that environmental policy and strategic incentives are the only reasons to deviate from a balanced budget path. At the beginning of each period, the acting government determines the vector of public good provision, (g_t, f_t). Subsequent governments cannot be pre-committed to provide a specific bundle in future periods.

[16]Note that regarding its interpretative value, my approach to model voter preferences is more in line with the models of bipartisan systems by Alesina and Tabellini (1990) and Persson and Svensson (1989), as every voter's preference is perfectly aligned with either party E or I. By contrast, in the median voter perspective taken by Tabellini and Alesina (1990), an arbitrary politician always implements the decisive median voter's internalization preference. Thus, the politician merely acts as the voters' agent and does not represent any party's agenda. Analytically, the bipartisan approach is expedient because all possible realizations of θ_i are ex-ante known.

In this framework, political economy incentives arise from uncertainty about the identity of the party in office after voting at the beginning of the second period. For reelection uncertainty to arise, there must be some exogenous factor which influence the majority's decision to vote for either party I or E. Tabellini and Alesina (1990) argue that this is the case when, for instance, the (perceived) costs of voting participation or the eligibility to participate in elections change. Both reasons may be relevant in the context of environmental pollution and climate change. On the one side, environmental catastrophes caused by climate change could be the catalyst for people, who previously abstained to cast their vote in future elections. Similarly, the recent surge of global movements like *Fridays for Future* indicates that adolescents' awareness for environmental issues may be comparably high (e.g., see Hornsey et al., 2016 or Lewis et al., 2019). Thus, with several jurisdictions across the globe, including California and France, currently discussing the possibilities of lowering the legal age of voting, eligibility could also have a substantial effect on the outcome of future elections. In either case, if θ_i differs between periods, the incumbent government will be replaced in office through voting which will also affect the public goods bundle and emissions in the second period.

In the next section, I abstract from voting uncertainty and assume certain reelection of the first-period government to establish a benchmark for the main analysis in section 3.4. I also examine how the outcome under certain reelection compares against the social optimum.

3.3 Social planner's problem and certain reelection

The existing literature on the political economy of public debt acknowledges that the ruling party can strategically employ public debt in the first period to transfer spending capabilities from the second period – where, from their perspective, funds will not be used optimally – and increase current spending. Thus, the incumbent limits the future government's discretion over the second-period budget as debt has to be repaid before spending. Initially, I focus on the case where the government's identity remains unchanged, such that the incumbent is certain of reelection in the next period and maximizes their electorate's intertemporal welfare by smoothing provision of the public goods across periods. For this reason, in an economy without pollution, all parties would run a balanced budget whenever there is no uncertainty about being reelected (see Persson and Svensson, 1989, Alesina and Tabellini, 1990 or Tabellini and Alesina, 1990). This outcome under certain reelection coincides with the first-best level of public debt.

However, if the provision of g_t causes emissions and politicians do not consider the true extent of environmental damages, public debt under reelection certainty is no longer equal to the first-best solution. To show this, first consider that the party with preferences θ_i is in office in both periods, where i is either I or E. Hence, the decision maker can maximize welfare over all variables in advance such that the optimization problem of the government represented by party i can be written as

$$\max_{g_1,g_2,b} W^i = u(g_1) + u(1+b-g_1) + u(g_2) + u(1-b-g_2) \\ - \theta_i\Big(D_1(g_1) + D_2(\gamma g_1 + g_2)\Big). \tag{3.4}$$

In (3.4), the public budget constraints (3.3a) and (3.3b) are already substituted for f_t. The respective first-order conditions read

$$\partial W^i/\partial g_1 = u'(g_1) - u'(f_1) - \theta_i\Big(D_1'(g_1) + \gamma D_2'(\gamma g_1 + g_2)\Big) = 0, \tag{3.5a}$$

$$\partial W^i/\partial g_2 = u'(g_2) - u'(f_2) - \theta_i D_2'(\gamma g_1 + g_2) = 0, \tag{3.5b}$$

$$\partial W^i/\partial b = u'(f_1) - u'(f_2) = 0. \tag{3.5c}$$

Let $D_1' + \gamma D_2'$ be the cumulative marginal damage of first-period emissions, whereas D_2' denotes the cumulative marginal damage of second-period emissions. Then, (3.5a) to (3.5c) lend basis for the following result which is proved in Appendix 3.6.1.

Proposition 3.1 *Whenever the cumulative marginal damage of emissions decreases [increases] over time, it is socially optimal to accumulate a positive level of savings [public debt] in the first period. Under certain reelection, any politician with preferences $\theta_i \neq 1$ deviates from the socially optimal budget balance. In particular, if the politician ignores pollution damages ($\theta_i = 0$), there is no incentive to deviate from a balanced budget ($b = 0$).*

Proposition 3.1 has two important implications which affect the subsequent analysis. First, it is socially optimal to deviate from a balanced budget and issue public debt or accumulate savings depending on how the cumulative marginal damage of emissions evolves over time. Hence, a balanced budget rule may be suitable to eliminate inefficient strategic behavior, yet, can never restore the first-best solution if persistent environmental pollution is taken into account. In case of decreasing cumulative marginal damages, emissions are more harmful, the earlier they are released into the atmosphere. Thus, welfare is maximized by postponing spending on the polluting good to the later period. The opposite intuition applies if cumulative marginal damages increase over time.

Second, when the damages from a stock pollutant are not fully internalized by the ruling party, the government will not implement the optimal level of public debt under certain reelection. Therefore, the public budget under certainty is at most second-best and might even be less efficient than the outcome under voting with uncertain reelection as will be shown in Section 3.4.3.

However, it is not possible to generally determine whether the partially internalizing government chooses inefficiently *high* or *low* debt. In Appendix 3.6.5, I derive that

$$\operatorname{sign}\left[\frac{\partial b}{\partial \theta_i}\right] = -\operatorname{sign}\Big[\big(D_1' + \gamma D_2' - D_2'\big)\big(-u''(f) + \theta_i \gamma D_2''\big) \\ + \big(D_1' + \gamma D_2'\big)\big(-u''(g_2) + \theta_i D_2''\big) - D_2'\big(-u''(g_1) + \theta_i D_1'' + \theta_i \gamma^2 D_2''\big)\Big], \quad (3.6)$$

where f has been substituted for $f_1 = f_2$ due to (3.5c). Since $g_1 = g_2$ if the party in office ignores the environmental damage, it is straightforward to see that the sign of $\partial b/\partial \theta_i$ only depends on the first product on the RHS of (3.6) when $\theta_i = 0$. Thus, for small increases in θ_i close to zero, the government starts to accumulate public debt [savings] whenever it is socially optimal to run a negative [positive] public budget. Yet, as θ_i increases, the sum of the last two terms on the RHS of (3.6) can attenuate or even overturn this effect. As a result, a politician, who is certain of reelection and partially internalizes pollution damages, may even choose an inefficiently high level of public debt or savings, respectively.

This is illustrated by Figure 3.1 using the numerical results from a quadratic specification of the model with

$$u(x) = \alpha x - \frac{\beta}{2}x^2, \qquad \text{with} \quad \alpha \geq 1,\, \beta > 0, \quad (3.7)$$

for both public goods g_t and f_t, as well as the quadratic damage function

$$D_t(x) = \frac{\delta_t}{2}x^2, \qquad \text{with} \quad \delta_t > 0\,\forall t. \quad (3.8)$$

While $\alpha = \beta = 1$ and $\gamma = 0.6$ for simplicity, the individual graphs in Figure 3.1 depict the level of public debt under certain reelection as a function of θ_i for variations of the damage parameters δ_t. These results suggest that, under increasing [decreasing] cumulative marginal damages, public debt can become highest [lowest] under partial internalization, $\theta_i \in (0, 1)$ and decrease [increase] again before reaching the first-best level in $\theta^* = 1$.

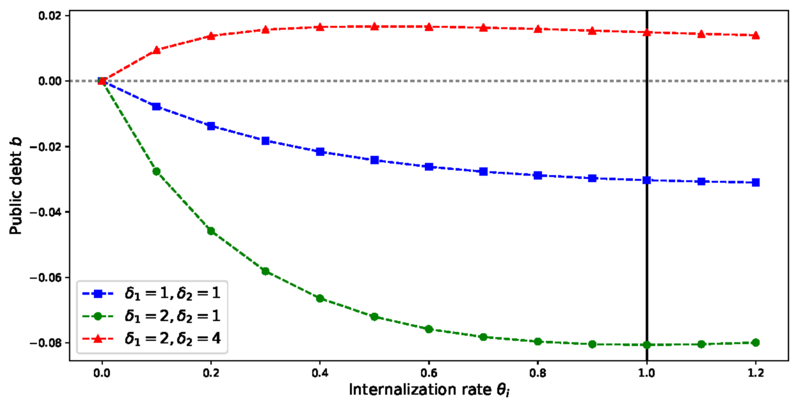

Figure 3.1: Level of public debt under certain reelection as a function of the government's internalization preference θ_i for various damage parameters δ_t

Any politician, who internalizes at least part of the environmental damages, acknowledges that spending on the polluting good should be postponed to the second period if the cumulative marginal damage of emissions decreases over time ($D'_1 + \gamma D'_2 > D'_2$) and accumulates public savings. However, if pollution damages are relatively high, it may be optimal to not just postpone but cut provision of the polluting good in both periods and instead increase spending on the clean good under full damage internalization. Consequently, a politician who does not consider the true extent of environmental damages may overestimate the value of second-period provision of the polluting good and, thus, save an inefficiently high amount for second-period spending on G. An analogous logic applies when the cumulative marginal damage of emissions increases over time ($D'_1 + \gamma D'_2 < D'_2$) such that positive public debt becomes optimal as depicted by the red graph in Figure 3.1.

To summarize these findings, when the government misjudges the true extent of pollution damages (both in the case of over- and under-internalization), public debt under certain reelection is no longer first-best, but can be either inefficiently high or low in comparison to the social optimum.

3.4 Recursive solution under reelection uncertainty

3.4.1 Political decision in the final period

To answer the central question of this chapter – how reelection uncertainty affects the levels of public debt, pollution and welfare – I employ a recursive approach by solving the second-period government's decision problem first. At the beginning of the second period, public debt (or savings), b, as well as past emissions from provision of g_1 are already predetermined by the previous government's decisions. Hence, the second-period government chooses the public goods bundle (g_2, f_2) to maximize its objective function by solving

$$\max_{g_2} W^2 = u(g_2) + u(1 - b - g_2) - \theta_2 D_2(\gamma g_1 + g_2), \tag{3.9}$$

where provision of the clean good, f_2, has been substituted for by $1-b-g_2$ according to budget constraint (3.3b). The internalization parameter θ_2 either equals θ_E or θ_I, depending on which party is in office at time $t = 2$. From the corresponding first-order condition

$$u'(g_2) - u'(1 - b - g_2) - \theta_2 D_2'(\gamma g_1 + g_2) = 0, \tag{3.10}$$

optimal provision levels of both public goods can be derived implicitly as

$$g_2^v = g_2(b, \theta_2, g_1) \quad \text{and} \quad f_2^v = 1 - b - g_2^v = f_2(b, \theta_2, g_1). \tag{3.11}$$

The expressions in (3.11) reveal that the second-period decision is contingent on the acting government's pollution awareness, θ_2, but also 'inherited' variables, namely public debt, b and the stock of emissions which remains from provision of the polluting good in the first period, γg_1.[17] If $\theta_2 = 0$, the second-period government ignores the externality and chooses provision of g_2 and f_2 such that marginal utilities are equal (implying $g_2 = f_2$ in a specification with identical utility functions and equal preferences for both goods). In this case, the stock of pollution remaining from first-period provision of g_1 also becomes irrelevant for the allocation in $t = 2$ and the expressions are identical to the reaction functions defined by Tabellini and Alesina (1990) for a politician who values both public goods equally.

Applying the implicit function theorem to equation (3.10), the marginal effect of the stock of emissions on the provision of the polluting good in $t = 2$ may be derived as

$$\frac{\partial g_2^v}{\partial g_1} = \frac{\gamma \theta_2 D_2''(\gamma g_1 + g_2^v)}{u''(g_2^v) + u''(f_2^v) - \theta_2 D_2''(\gamma g_1 + g_2^v)} \in (-1, 0], \tag{3.12}$$

considering that $u''(\cdot) < 0$ and $D_2''(\cdot) > 0$. Hence, the second-period government will never offset the entire increase in first-period emissions, even if pollution does not

[17] Since γ is an exogenously given parameter, I do not explicitly specify it as argument of g^v and f^v. Still, g_1 only affects the second-period outcome if $\gamma > 0$.

decay at all. Analogously, differentiating the right-hand expression in (3.11) gives the partial effect of g_1 on demand for the clean good equal to

$$\partial f_2^v / \partial g_1 = -\partial g_2^v / \partial g_1 \geq 0. \tag{3.13}$$

Ceteris paribus, higher provision of the polluting good in the first period will also increase marginal damages in the second period creating an incentive for government 2 to shift funds away from G and instead increase provision of the clean good, F. The internalization parameter θ_2 defines how elastic this reaction will be. The higher the second-period government's internalization preference is, the stronger it responds to a larger stock of inherited pollution.

Finally, the total differentials of (3.11) can also be arranged to obtain the marginal effect of debt on second-period provision of the two public goods as

$$\frac{\partial g_2^v}{\partial b} = -\frac{u''(f_2^v)}{u''(g_2^v) + u''(f_2^v) - \theta_2 D_2''(\gamma g_1 + g_2^v)} \in (-1, 0), \tag{3.14}$$

and

$$\frac{\partial f_2^v}{\partial b} = -\Big(1 + \frac{\partial g_2^v}{\partial b}\Big) \in (-1, 0). \tag{3.15}$$

The marginal effect of public debt on both goods is negative and on the interval $(-1, 0)$ as higher debt reduces the overall budget available in $t = 2$. While (3.12) and (3.13) show that the second-period decision maker will not react to increased pollution in $t = 1$ if they ignore the climate externality ($\theta_2 = 0$), any government has to respond to higher borrowing by cutting provision according to (3.14) and (3.15). However, how a tightened budget affects spending on either good depends on θ_2 once more.

3.4.2 Political decision in the first period

The identity of the first-period government is ex-ante known and denoted by θ_1 which, again, is drawn from the set $\{E, I\}$. However, under voting uncertainty, θ_1 does not necessarily coincide with θ_2. Thus, the incumbent government maximizes its expected intertemporal welfare, W_1, over the decision variables (g_1, f_1, b). Since reaction functions g_2^v and f_2^v also depend on the unknown internalization parameter

θ_2, the incumbent's optimization problem in $t = 1$ equals

$$\max_{g_1,b} \mathbb{E}\big\{W^1\big\} = u(g_1) + u(1+b-g_1) - \theta_1 D_1(g_1) \\ + \mathbb{E}\Big\{u(g_2^v) + u(f_2^v) - \theta_1 D_2(\gamma g_1 + g_2^v),\Big\} \tag{3.16}$$

where g_2^v and f_2^v are determined by (3.10) to (3.15). Note that D_2 is still multiplied by θ_1 as the internalization preference of the incumbent party remains constant over time. If entrance into the political 'market' is restricted to parties E and I (i.e., either one of them will take office in the second period) and I assume that the first-period government is reelected by a given probability $\pi \in [0,1]$ (and loses office with probability $1-\pi$, respectively), the maximization problem in (3.16) can be expressed without the expectations operator as

$$\max_{g_1,b} \mathbb{E}\{W^1\} = u(g_1) + u(1+b-g_1) - \theta_1 D_1(g_1) \\ +\pi\Big\{u\big[g_2(b,\theta_1,g_1)\big] + u\big[f_2(b,\theta_1,g_1)\big] - \theta_1 D_2\big[\gamma g_1 + g_2(b,\theta_1,g_1)\big]\Big\} \\ +(1-\pi)\Big\{u\big[g_2(b,\theta_2,g_1)\big] + u\big[f_2(b,\theta_2,g_1)\big] - \theta_1 D_2\big[\gamma g_1 + g_2(b,\theta_2,g_1)\big]\Big\}, \tag{3.17}$$

where $\theta_1 \neq \theta_2$. For the sake of tractability, I assume that it is ex-ante known that $\theta_1 \neq \theta_2$, i.e., the incumbent government will be superseded with certainty in the second period and, thus, $\pi = 0$. This approach with alternating governments is similar to Persson and Svensson (1989) and Alesina and Tabellini (1990). I will still refer to this scenario as the outcome under voting uncertainty to clearly discern it from certain reelection. For $\pi \in (0,1)$, the incumbent's optimal behavior is a weighted average between the two extreme outcomes.

For $\pi = 0$, the first-order condition of the maximization problem in (3.17) with regard to provision of the polluting good is given by

$$u'(g_1) - u'(1+b-g_1) - \theta_1\Big(D_1'(g_1) + \gamma D_2'(\gamma g_1 + g_2^v)\Big) \\ + \frac{\partial g_2^v}{\partial g_1}(\theta_2 - \theta_1) D_2'(\gamma g_1 + g_2^v) = 0. \tag{3.18}$$

The respective condition for public debt follows as

$$u'(1+b-g_1) - u'(f_2^v) + \frac{\partial g_2^v}{\partial b}(\theta_2 - \theta_1) D_2'(\gamma g_1 + g_2^v) = 0, \tag{3.19}$$

where in (3.18) and (3.19), I make use of the equality

$$u'(g_2^v) - u'(f_2^v) - \theta_1 D_2'(\gamma g_1 + g_2^v) = (\theta_2 - \theta_1) D_2'(\gamma g_1 + g_2^v), \tag{3.20}$$

which can be obtained from expanding and rearranging (3.10). The last summands on the LHS of (3.18) and (3.19) capture the political economy incentives under uncertainty and vanishes when $\theta_1 = \theta_2$, i.e., in the certain reelection scenario. From (3.5c), it is known that any politician would prefer constant provision of the clean good over time if reelection is certain. Since $\partial g_2^v / \partial b$ is always negative, (3.19) implies that first-period spending on the clean good exceeds [falls short of] f_2 if the incumbent prefers a higher [lower] internalization rate than their successor. Similarly, any incumbent who ignores the externality would choose $g_1 = f_1$ in case of certain reelection. However, (3.18) reveals that provision of the polluting good in $t = 1$ decreases relatively to the clean good if the future government prefers a higher internalization rate even if the incumbent ignores pollution damages. In the opposite case, if $\theta_1 > \theta_2$, strategic incentives can drive the incumbent to increase g_1 relative to f_1 which counters the incumbent's intrinsic internalization incentive given by the third term on the LHS of (3.18).

While the total effects of uncertainty on public debt and provision of the polluting good are not yet clear from this initial inspection of the incumbent's first-order conditions, it is already apparent that there are two intertemporal interactions between the incumbent and future government in the model with stock pollution. The first occurs because the incumbent can influence future spending by issuing debt or accumulating savings. I will refer to this as the *budget* interaction which is already well known in the political economy literature and typically causes inefficient deficit spending in the first period. The second interaction is less deliberate and is a result of slowly decaying emissions. This *emission* interaction may not only discipline the future government but also the incumbent because the stock of pollution, unlike public debt in the underlying model by Tabellini and Alesina (1990), can also affect the composition of the public goods bundle in the future.

3.4.3 Strategic effects on public debt

The strategic effects on debt depend on both the budget and the emission interaction. First, I examine how voting uncertainty affects the public budget in comparison to the certain reelection outcome and, then, turn to analyze how the impact on budget efficiency differs from the findings in a framework without pollution like the model by Tabellini and Alesina (1990).

For tractability, I derive all subsequent results for the quadratic specification of the model given by (3.7) and (3.8). This has the advantage that preferences can vary widely between parties, e.g., when party E prefers close to full internalization ($\theta_E \to 1$), whereas party I tends to ignore the externality ($\theta_I \to 0$). In Appendix 3.6.2, I derive the following result.

Proposition 3.2 *Consider the quadratic specification of the model. Compared to the case with certain reelection ($\theta_1 = \theta_2$), reelection uncertainty ($\theta_1 \neq \theta_2$) always creates a strategic incentive to issue more public debt in the first period regardless of the identity of the incumbent government, θ_1. This effect becomes more pronounced, the more θ_2 deviates from θ_1.*

As stated by Proposition 3.2, reelection uncertainty creates a strategic incentive to issue public debt for any incumbent government which increases with the parties' disagreement on optimal internalization. If party E is in office in the first period, i.e., $\theta_1 = \theta_E > \theta_I = \theta_2$, the environmentalists anticipate that the future industrialist government will overspend on the polluting good while providing too little of the clean good from the incumbent's perspective. This creates an incentive to reduce the amount of public savings (or even to accumulate debt) and spend more on the clean good today. If the first-period government is constituted by industrialists, I, the incentives are similar expect that, in their opinion, the future environmentalist government will spend too much on the clean good while providing an insufficient amount of the polluting good. They will also divert funds from the second period and increase spending on the clean good.

However, counter to intuition, higher debt does not necessarily translate into increased spending on the polluting good even for an industrialist incumbent as will be shown by Proposition 3.3 in the next section if $\gamma > \tilde{\gamma}$. This results from the fact that public debt is no longer the only channel through which incumbent and future government interact. Due to persistent stock pollution, provision of the polluting good cannot increase freely but has to take future reactions to a larger pollution 'inheritance' into account. Since the optimal composition of the public goods bundle in the first period is implicitly defined by (3.18), the potential to 'sink' excess borrowing into the clean good is also limited. Therefore, the value of strategic debt is lower due to the emission interaction. In the model without pollution by Tabellini and Alesina (1990), the incumbent simply scales up provision of both goods to maintain a constant ratio between g_1 and f_1.

Figure 3.2 illustrates the results from a numerical analysis of the quadratic model which also indicates that the incentive to issue strategic debt diminishes as the atmospheric persistence of emissions increases. For simplicity, the example is computed for the parameters $\alpha, \beta, \delta_1, \delta_2$ equal to unity. Each panel depicts public debt in $t = 1$ as a function of the second-period internalization rate, θ_2, for an ex-ante given preference θ_1 and various emission persistence rates, γ. In all cases, public debt is minimized when $\theta_1 = \theta_2$ which corresponds to certain reelection. In addition, the graphs become flatter as the atmospheric persistence of emissions increases. When the incumbent has to afford higher deficit spending in the first period at the expense of leaving a very persistent stock of emissions to the second-period government, strategic debt accumulation becomes less attractive.

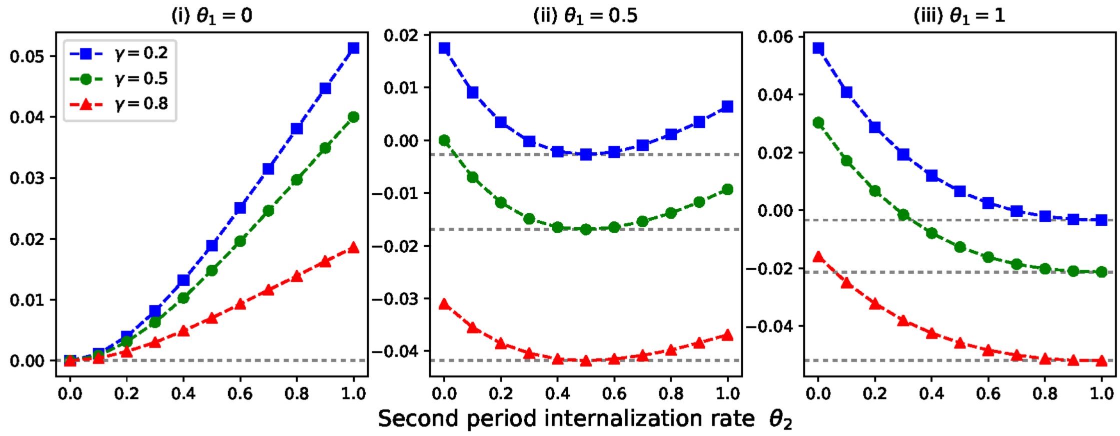

Figure 3.2: Public budget balance at the end of the first period

Note that Proposition 3.2 is not affected by how the cumulative marginal damage from emissions evolves over time in contrast to the optimal policy given by Proposition 3.1. Whether optimal debt (or debt under certain reelection, respectively) should be negative or positive is only contingent on the pollution externality. The effect of reelection uncertainty, however, is driven by the budget interaction which outweighs the emission interaction.[18] Hence, the incumbent will always accumulate more debt when the incumbent and future governments disagree on the optimal internalization rate, i.e., when the absolute value of $\Delta = (\theta_2 - \theta_1)$ increases.

The effect of voting uncertainty on public budget efficiency in comparison to the certain reelection benchmark is no longer as clear cut as in Tabellini and Alesina (1990). In their analysis, voting is always associated with an inefficiency as first-best debt, b^*, and debt in the case of certain reelection, b^c, coincide. Since b^c can exceed or fall short of b^* in the model with stock pollution, a number of different results

[18] This is implicitly evident from Proposition 3.2. Otherwise, public debt would not always increase when θ_2 deviates from θ_1, but only if $D_1' + \gamma D_2' < D_2'$.

are possible in my analysis. On the one hand, if the cumulative marginal damage of emissions decreases over time, the social planner would accumulate public savings. If partially-internalizing politicians prefer *lower* savings under certain reelection than socially optimal ($b^* < b^c \leq 0$), e.g., when θ_1 close to zero, uncertainty creates an additional incentive to issue debt such that public debt under reelection uncertainty, b^v, is even less efficient ($b^* < b^c < b^v$). Strategic incentives can even lead to $b^v > 0$ despite savings being optimal. However, from the numerical analysis underlying Figure 3.1, it is also known that a politician, who does not acknowledge the full extent of emission damages, may accumulate inefficiently *high* savings under certain reelection, i.e., $b^c < b^* < 0$. Under these circumstances, a strategic incentive to issue debt leads to $b^c < b^v$, meaning that voting uncertainty can also shift the budget balance closer to the first-best level. Consequently, certain reelection would only result in a third-best budget.

On the other hand, if the cumulative marginal damage from emissions is higher in the second period, the first-best solution demands for a positive level of public debt, $b^* > 0$. If the incumbent issues an inefficiently low amount of debt, as is always the case for θ_1 close to zero, a strategic increase in public debt due to voting uncertainty ($b^v > b^c$) can result in a more efficient budget. In contrast, if public debt is already inefficiently high under certain reelection, e.g., for $\theta_1 = 0.5$, $\delta_1 = 2$ and $\delta_2 = 4$ in Figure 3.1, the strategic incentive to issue debt increases the deviation from the social optimum such that the public budget under voting is third-best and certain reelection is preferable from a fiscal perspective.

Whether public debt under certain reelection of a politician who misjudges the true extent of emission damages is inefficiently high or low, depends on the parameters of the utility and damage functions. Therefore, it is generally not possible to determine if voting uncertainty is associated with efficiency gains or exacerbates the budget inefficiency. Nonetheless, my findings shed a more favorable light on reelection uncertainty in contrast to Tabellini and Alesina (1990), who find that uncertainty always causes an inefficiency in the model without stock pollution. Examples for all cases discussed above can be found in Table 3.1.

3.4.4 Strategic effect on first-period provision of the polluting good

Next, I will identify the strategic incentives affecting provision of the polluting good in the first period when reelection is uncertain. As already hinted at above, the direction of the strategic effect depends on whether the budget interactions dominates the emission interaction and vice versa. Appendix 3.6.3 proves:

Proposition 3.3 *Consider the quadratic specification and assume* $\gamma > [<]\tilde{\gamma} = 1/3$*. Compared to the case with certain reelection* ($\theta_1 = \theta_2$)*, reelection uncertainty* ($\theta_1 \neq \theta_2$) *reduces [increases] first-period spending on the polluting good regardless of the identity of the incumbent government,* θ_1*. This effect becomes more pronounced, the more* θ_2 *deviates from* θ_1*.*

The insight from Proposition 3.3 is rather striking. Whether to strategically increase first-period provision or abate the polluting good due to voting uncertainty does not depend on the incumbent's identity, i.e., θ_1, but on the atmospheric persistence of emissions, γ. As also noted by Voß (2014), the incumbent government can appear to be 'greener' than they actually are under reelection uncertainty. However, my analysis of the integrated fiscal-climate model shows that this effect only occurs if emissions are sufficiently persistent.

Intuitively, it may be expected that, whenever the potential second-period government is less concerned about environmental damages and $\gamma > \tilde{\gamma}$, an incumbent from party E wants to hedge against excessive pollution in the future. The incumbent E is aware that a higher provision of g_1 will not just limit future emissions by draining funds from the second period, but also causes pollution damages in both periods. Knowing that their successor from party I will always produce too much pollution from the environmentalists' perspective, the incumbent E can reduce the second-period stock of pollution by providing less of the polluting good in the first period. This effect attenuates the incentive to shift funds to the first period whenever the incumbent is 'greener' than the future government.

However, the emission-abating effect of uncertainty also occur for $\gamma > \tilde{\gamma}$ when the incumbent prefers a lower internalization rate than the potential future government. If, initially, the industrialists' party I is in office, they anticipate that their successor from party E, who always provides too little of the polluting good from the incumbent's perspective, will provide even less when the stock of emissions inherited from the previous period is already high. By abstaining from spending on the polluting good in the first period and, thus, leaving more funds and fewer emissions, the incumbent ensures that the second-period government E does not cut provision of g_2 too drastically. Hence, even a politician who prefers a low internalization rate, or completely ignores the externality, decides to provide less of the polluting good in $t = 1$ than when reelection is certain .

Since there are two strategic interactions between the incumbent and future government in the integrated model, the incentive to issue debt and increase first-period provision outweighs the emission interaction if the atmospheric persistence of emissions is below the threshold $\tilde{\gamma}$. In this case, any incumbent, even the environmentalists, values the benefit from deficit spending on their preferred public goods bundle more than additional second-period pollution damages caused first-period emissions as they will have mostly decayed until the second period. Hence, reelection uncertainty always increases emissions in the first period if $\gamma < \tilde{\gamma}$.

Figure 3.3 illustrates the insight from Proposition 3.3 in a numerical example. The graphs depict first-period provision of the polluting good, g_1, as a function of the expected internalization rate, θ_2, for ex-ante known realizations of θ_1. When computing the numerical model for a small atmospheric persistence parameter, here $\gamma = 0.2 < \tilde{\gamma}$, provision of the polluting good in $t = 1$ indeed increases if θ_2 diverges from θ_1. In this case, first-period emissions decay rapidly and the emission interaction is relatively weak. Hence, the incumbent can transfer funds to the first period in order to increase provision of both public goods without having to fear that, if $\theta_2 > \theta_1$, their successor will severely cut spending on g_2 as the inherited stock of emissions, γg_1, remains small. On the other hand, if $\theta_2 < \theta_1$, the incumbent is aware that abstaining from the polluting good in the first period will not significantly reduce damages in the future as the second-period stock of emissions is primarily driven by their successor's decisions. As a result, for persistence rates below the threshold $\tilde{\gamma}$, the budget interaction dominates the strategic considerations affecting provision of g_1. In contrast, for persistence rates above the threshold $\tilde{\gamma}$, e.g., $\gamma \in [0.5, 0.8]$ in Figure 3.3, the emission interaction dictates the strategic provision of the polluting good and provides an incentive to cut g_1 whenever $\theta_1 \neq \theta_2$. The numerical examples suggest that the magnitude of the response increases as the stock pollutant becomes more persistent.

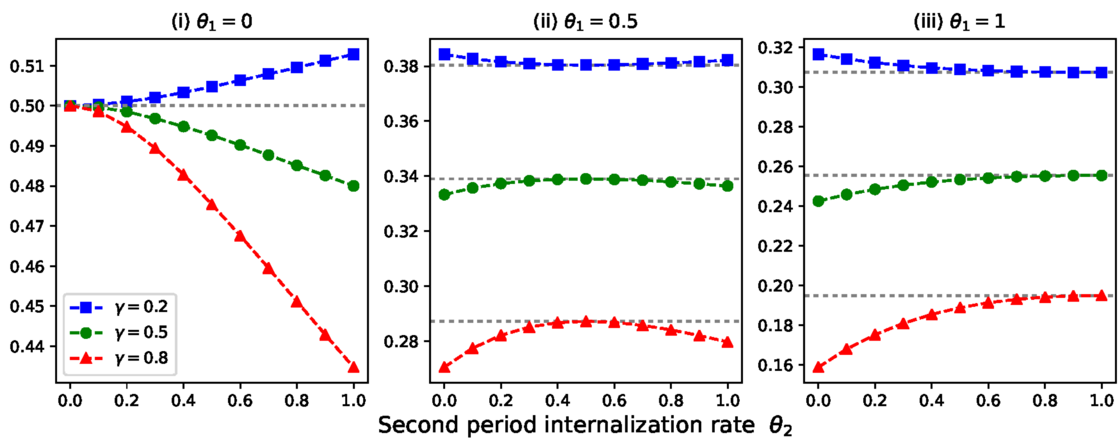

Figure 3.3: Provision of polluting public good in the first period

The specification of the damage function implicitly assumes that emissions increase one-to-one with the quantity of g_t provided by the government. Hence, I find that reelection uncertainty improves environmental quality in the first period if emissions are sufficiently persistent, i.e., $\gamma > \tilde{\gamma}$. In Appendix 3.6.5, I derive that $\gamma > \tilde{\gamma}$ also is a sufficient condition for g_1 to decrease in θ_i under certain reelection. This implies that a partially-internalizing politician would provide an inefficiently high quantity of the polluting good when certain of reelection. Hence, a strategic decrease in g_1 can improve welfare in the first period. In contrast, if the first-period government demands over-internalization (i.e., $\theta_1 > 1$), provision of g_1 is already below the first-best level in the certain-reelection benchmark such that voting uncertainty aggravates under-provision even further.

3.4.5 Intertemporal pollution damages under reelection uncertainty

Whether the emission-abating effect of reelection uncertainty in the first period also translates to overall lower intertemporal pollution damages, further depends on the second-period decisions. Providing less of the polluting good in the first period directly reduces the (marginal) damage from pollution in the first period, results in a lower stock of inherited emissions at the beginning of the second period and increases provision of g_2 according to (3.12). To what extent the second-period government reacts to the incumbent's emission abatement also depends on their pollution awareness, θ_2.

In order to systematically assess this question, I determine how total intertemporal pollution damages, as given by

$$TD = D_1(g_1) + D_2(\gamma g_1 + g_2), \tag{3.21}$$

are affected by voting uncertainty. Note that (3.21) assumes the social planner's perspective with full internalization, i.e., TD amounts to the true (or global) welfare loss from pollution. To determine the total effect in (3.21), I first identify the effect of reelection uncertainty on second-period provision which can be employed to proof the following proposition in Appendix 3.6.4:

Proposition 3.4 *Consider the quadratic specification and assume $\gamma < [>] \tilde{\gamma} = 1/3$. Compared to the case of certain reelection ($\theta_1 = \theta_2$), reelection uncertainty increases [decreases] total intertemporal pollution damages if $\theta_1 > \theta_2$ [$\theta_1 < \theta_2$ and $(2 - \gamma - 3\gamma^2)(\theta_2\delta_2)^3 \gtrless 0$ is sufficiently large]. This effect becomes more pronounced, the more θ_2 deviates from θ_1.*

Considering practical implications for climate policy, the most important conclusion from Proposition 3.4 is that the expected total welfare loss from pollution damages can decrease as a direct result of voting uncertainty when emissions are rather persistent and the incumbent competes against a green(er) party, i.e., $\gamma > \tilde{\gamma}$ and $\theta_2 > \theta_1$. This case appears most relevant when, due to a rising concern for environmental issues in wealthy industrialized countries, green parties' appeal to voters is growing (see e.g., Grant and Tilley, 2019) and incumbent governments are still comprised of centrist or conservative parties which, traditionally, might prefer less stringent climate policy than their green counterparts. In this case, the incumbent I abates emissions in anticipation of their potential successor's strong response to inheriting a high stock of pollution. Additionally, if party E actually takes office in the second period, they will also provide less of the polluting good than party I would when reelected due to $\theta_E > \theta_I$. Thus, voting leads to lower pollution damages in both periods which results in a lower overall welfare loss from pollution damages.

In contrast, if the competing party's pollution awareness is lower than the incumbent's and emissions decay relatively quickly, i.e., $\theta_2 < \theta_1$ and $\gamma < \tilde{\gamma}$, strategic incentives lead to higher emissions in the first period than caused in the case of certain reelection. Coupled with a higher second-period provision of the polluting good by the environmentally less aware successor, TD would increase as a result of reelection uncertainty.

Under the conditions of Proposition 3.4, second-period provision of the polluting good, g_2, is decreasing in Δ, such that second-period emissions are highest [lowest] in $\theta_2 = 0[= 1]$ for any ex-ante known internalization preference θ_1. This result contrasts with the findings for public debt and first-period provision of the polluting good. Both of these variables reach their minimum [maximum] in the certain reelection-outcome and increase [or decrease in the case of g_1 when $\gamma > \tilde{\gamma}$] with voting uncertainty regardless of the competitors identity, θ_2.

Figure 3.4 illustrates the results from Proposition 3.4 in the numerical model. Notably, for the parameter specification defined above, TD is always decreasing, including the case of atmospheric persistence levels is below the threshold $\tilde{\gamma}$, e.g., as depicted for $\gamma = 0.2$. Even though the incumbent government would strategically increase g_1 according to Proposition 3.3, a 'green' second-period government can still compensate for the hike in $D(g_1)$ by abating g_2 as the stock of pollution decays relatively quickly.

The 'optimal' total welfare loss from pollution implemented by the social planner coincides with the level of pollution damages given by $\theta_1 = \theta_2 = 1$ in the right-most panel of Figure 3.4. Thus, while voting can reduce pollution damages below

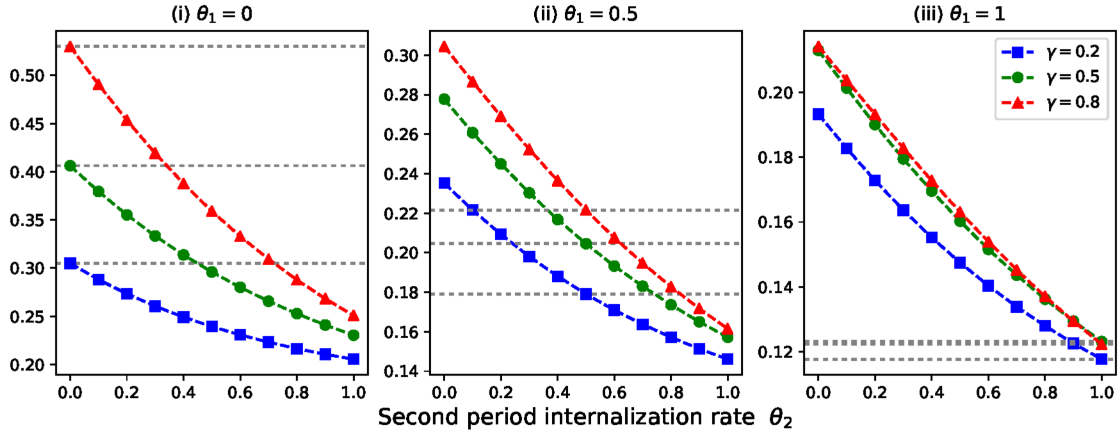

Figure 3.4: Total welfare loss from pollution

the certain reelection benchmark, inefficient over-pollution always occurs if at least one party prefers only partial internalization and preferences are restricted to the interval $\theta_i \in [0, 1]$. However, part (ii) of Proposition 3.4 also holds if the second-period government is a proponent of over-internalization, i.e., $\theta_2 > 1$. Then, reelection uncertainty further attenuates emission damages, moving the economy closer to the first-best level of pollution. Eventually, though, inefficient under-pollution occurs if the second-period government's internalization preference is extreme enough. This case is most likely to occur when the incumbent prefers a high internalization rate such that the outcome under certain reelection is already close to the social optimum.

3.4.6 Total welfare effect of strategic interactions

In order to assess the total welfare impact of voting, recall that reelection uncertainty can either attenuate or exacerbate the budget inefficiency and affects provision of the polluting good in both periods. Therefore, the total impact is ambiguous and can generally not be determined analytically for all relevant cases. From the social planner's perspective, any government with $\theta_1 < 1$ provides an inefficiently high quantity of the polluting good under certain reelection. For persistence rates below the threshold $\tilde{\gamma}$, voting further increases over-provision of g_1. In this case, the intertemporal sum of pollution damages increases due to voting uncertainty when $\theta_2 < \theta_1$. If excessively high pollution is further accompanied by a strategic budget inefficiency, total welfare decreases as a result of reelection uncertainty. In this case, certain reelection is to be preferred in terms of welfare optimization.

However, the latter result can be overturned when the competitor demands a higher internalization rate than the incumbent ($\theta_2 > \theta_1$) and emissions are sufficiently persistent ($\gamma > \tilde{\gamma}$). Then, the first-period government provides less of the polluting good due to strategic incentives, reducing the deviation from the first-best allocation, while the intertemporal sum of pollution damages also shrinks as a result of uncertain reelection under the conditions of Proposition 3.4. If strategic debt accumulation decreases the budget inefficiency, the overall welfare effect of voting uncertainty is clearly positive. Yet, even if the budget becomes less efficient, it can be outweighed by the positive welfare effect of lower pollution. The net effect then depends on the quantitative magnitudes of the individual effects on public debt, first-period provision of the polluting good and cumulative pollution damages.

While this result may appear vague, it carries a significant normative implication. In the existing literature on the political economy of public debt ignoring environmental pollution (with the exception of Peletier et al., 1999), voting uncertainty leads to inefficient strategic incentives. This result can also arise in my model with stock pollution. Yet, the opposite may also be true due to the emission interaction and normative reasons to deviate from a balanced budget. Hence, from an efficiency perspective, the unambiguous superiority of certain reelection over voting is no longer tenable and, in fact, it may be efficient to foster competition for political offices.

To gain some intuition on the possible outcomes, Table 3.1 provides the results from computation of the numerical model for various damage function parameters and internalization preferences. In the first specification, I assume $\delta_1 = \delta_2 = 1$ (rows 1 to 7) such that the cumulative marginal damage from emissions decreases over time. Hence, the social planner spends less on the polluting good in the first than in the second period and accumulates savings. Rows 2 and 5 show that public savings are inefficiently low when a politician with either $\theta_1 = 0.2$ or $\theta_1 = 0.8$ is certain of reelection. Voting uncertainty increases the budget inefficiently regardless of whether the competitor for office in the second period demands higher, lower or even over-internalization. However, the efficient reduction of total pollution damages due to $\theta_2 > \theta_1$ in rows 3 and 4 outweighs the budget distortion and welfare is higher under voting than under certain reelection. As apparent from row 7, total pollution damages can become inefficiently low when the incumbent already implements an allocation close to the social optimum and the second-period government over-internalizes damages. In this case, welfare is only third-best in the presence of voting uncertainty and dominated by the certain reelection outcome.
Rows 8 to 10 in Table 3.1 also represent a case where the cumulative marginal damage of emissions decreases over time. Yet, since the first-period damage parameter is relatively high, public savings are higher under certain reelection of a partially

Table 3.1: Numerical comparison of first-best, certain reelection and uncertainty

	$\{\delta_1, \delta_2\}, \{\theta_1, \theta_2\}$		W	WL	b	g_1	TD
1	$\{1, 1\}, \{1, 1\}$	first-best	1.2660	–	-0.0303	0.2357	0.1236
2	$\{1, 1\}, \{0.2, 0.2\}$	reelection	1.1694	0.0966	-0.0137	0.4110	0.3190
3	$\{1, 1\}, \{0.2, 0.8\}$	voting	1.2252	0.0408	-0.0008	0.4006	0.2202
4	$\{1, 1\}, \{0.2, 1.5\}$	voting	1.2319	0.0341	0.0239	0.3809	0.1563
5	$\{1, 1\}, \{0.8, 0.8\}$	reelection	1.2632	0.0028	-0.0288	0.2644	0.1505
6	$\{1, 1\}, \{0.8, 0.2\}$	voting	1.2270	0.0390	-0.0131	0.2566	0.2132
7	$\{1, 1\}, \{0.8, 1.5\}$	voting	1.2592	0.0068	-0.0203	0.2602	0.1063
8	$\{4, 1\}, \{1, 1\}$	first-best	1.2292	–	-0.1250	0.1042	0.1085
9	$\{4, 1\}, \{0.6, 0.6\}$	reelection	1.2135	0.0157	-0.1275	0.1569	0.1773
10	$\{4, 1\}, \{0.6, 0.8\}$	voting	1.2191	0.0101	-0.1262	0.1565	0.1591
11	$\{1, 4\}, \{1, 1\}$	first-best	1.1373	–	0.0588	0.1961	0.0961
12	$\{1, 4\}, \{0.1, 0.1\}$	reelection	0.6321	0.5052	0.0282	0.4194	0.8435
13	$\{1, 4\}, \{0.1, 0.4\}$	voting	0.9910	0.1463	0.0539	0.3965	0.3907
14	$\{1, 4\}, \{0.1, 0.8\}$	voting	1.0919	0.0454	0.0916	0.3630	0.1996

Notes: Numerical results for the quadratic model specified in (3.7) and (3.8) with $\{\alpha, \beta, \gamma\} = \{1, 1, 0.6\}$; W denotes true welfare as perceived by an individual who fully internalizes emission damages; WL, b, g_1 denote the welfare loss in comparison to the first-best solution, public debt, first-period provision of the polluting good and total intertemporal pollution damages; 'reelection' and 'voting' scenarios refer to reelection probabilities of $\pi = 1$ and $\pi = 0$, respectively.

internalizing politician with $\theta_1 = 0.6$ than in the social optimum. The strategic incentive to increase debt under reelection uncertainty then reduces the deviation from the first-best budget balance. Together with a more efficient provision of the polluting good due to $\theta_2 > \theta_1$, this leads to welfare gains as a result of the strategic interactions in the voting economy.

In contrast, when the cumulative marginal damage increases over time as in rows 11 to 14, it is optimal to issue a positive level of public debt. If the incumbent party internalizes only a small fraction of pollution damages, public debt under certain reelection is inefficiently low. Voting uncertainty always increases public debt. While the budget balance can become more efficient if the parties do not disagree too much on the optimal internalization rate (row 13), the strategic incentive to issue debt may also increase the budget inefficiency when θ_2 is relatively high (row 14). For the parameter specification at hand, the welfare function is dominated by pollution damages such that voting still increases welfare in both cases and the certain reelection outcome is overall less efficient.

3.5 Conclusion

In this chapter, I build on the analytical framework by Tabellini and Alesina (1990) and introduce an environmental externality in their political economy model of public debt. Politicians allocate public funds in order to provide clean and polluting public goods which generate utility for their electorates. Provision of the polluting good also causes emissions which accumulate as a gradually decaying stock and cause a welfare loss. I find that, when politicians do not consider the true extent of pollution damages and disagree on the optimal internalization rate of emissions, the strategic dependencies between incumbent and future government are no longer restricted to a budget interaction but, additionally, an emission interaction occurs.

If emissions are sufficiently persistent, strategic interactions reduce provision of the polluting good in the first period, regardless of the incumbent government's own internalization preference. Since politicians, who only acknowledge part of the pollution damages, provide too much of the polluting good under certain reelection, voting increases environmental quality and, thereby, can generate welfare improvements. This strategic effect can be accompanied by a decrease in expected second-period pollution damages if the competing party demands a higher internalization rate than the incumbent which, in turn, can lead to an additional welfare gain. In contrast, if the competitor for office is less aware of the environmental externality than the incumbent, they will increase provision of the polluting good in the second period to a degree that over-compensates previous emission abatement in case they win the elections.

As in the underlying model by Tabellini and Alesina (1990) without pollution, I show that voting always creates a strategic incentive to increase public debt. However, in contrast to the previous literature, this incentives is not necessarily inefficient for two reasons. First, when emissions accumulate as persistent stock pollutant, there is a normative justification to deviate from a balanced budget. This is also the reason why, unlike in the analyses by Persson and Svensson (1989) and Alesina and Tabellini (1990), a balanced budget rule cannot be employed to restore efficiency in the economy with stock pollution. Second, partial internalization can lead the government to issue an inefficiently low amount of public debt in case of certain reelection. Thus, a strategic increase in public debt due to voting may improve the budget efficiency.

Consequently, strategic interactions arising in the voting economy harbor potential for efficiency gains which can turn reelection uncertainty attractive from a welfare-maximizing perspective. The strategic incentives are most pronounced when either the incumbent's chances to remain in office are low or if there is strong disagreement on the optimal internalization rate. Hence, the long-term impact of reelection uncertainty on climate policy is contingent on the political status quo. If the incumbent is rather reluctant to implement stringent environmental protection laws or has a bias towards GHG intensive industries, the growing appeal of environmentalist or green parties can 'force' current decision makers to commit to more climate friendly policies. This case appears especially relevant for wealthy, industrialized countries. While Voß (2014) provides illustrative anecdotal evidence from German politics, the newly elected Biden administration in the US also shows considerably greater commitment to climate policy than its predecessor. In the framework of this chapter, a green fringe party demanding radical emission abatement, yet not particularly likely to take office, can have the same impact on the incumbent's behavior as a more moderate centrist party with a high probability to win the elections.

In short, if environmental benefits are joined by efficient strategic debt or outweigh a potential budget inefficiency, voting leads to an overall welfare gain in comparison to certain reelection. This is a novel result which cannot be observed in the underlying model by Tabellini and Alesina (1990). To conclude, the integrated fiscal-climate model sheds a more favorable light on the implications of voting than a purely fiscal perspective.

To the best of my knowledge, this chapter conducts the first integrated analysis of the political economy interactions between environmental pollution and public debt. Naturally, my analysis is subject to a number of limitations which leaves several avenues for future research to explore. As a conceptual caveat, in order to compare the results of the certain reelection and voting scenarios against a welfare optimum, I have to make a normative judgment on the optimal internalization rate. This value can vary depending on whether we take a global or national perspective. However, the most notable limitation is that reelection probabilities remain exogenously fixed. Strategic incentives and interactions would certainly change if parties were able to influence these probabilities by committing to spending and emission targets. I also assume that all voters can identify with one of two parties which are identical except for their internalization preferences. In the model at hand, politicians gain no personal benefit from holding office, thereby, acting as perfect agents of their respective electorate. Additionally, public funds are exogenously given such that the second-period government cannot respond to higher debt liabilities by increasing taxation. In this context, emission taxes are of particular interest due to their potential to reap a double dividend. Since these limitations are necessary concessions to the analytical complexity of the multi-period model with various interactions, calibrated and empirical analyses may be especially valuable to gain further insight on this topic.

3.6 Appendix

3.6.1 Proof of Proposition 3.1

From first-order condition (3.5c), it becomes apparent that any government chooses $f_1 = f_2$ regardless of θ_i. Subtracting (3.5b) from (3.5a) and employing (3.5c), results in

$$u'(g_1) - u'(g_2) = \theta_i \Big[D_1'(g_1) + \gamma D_2'(\gamma g_1 + g_2) - D_2'(\gamma g_1 + g_2) \Big], \tag{3.22}$$

which defines the relation between g_1 and g_2. The sign of the RHS of (3.22) is positive [negative] if $D_1' + \gamma D_2' > [<] D_2'$. Since $u'(g_t)$ is decreasing due to $u''(g_t) < 0$, any politician with $\theta_i > 0$ (including the social planner with $\theta^* = 1$) provides $g_1 < [>] g_2$. Combining (3.3a) and (3.3b) and solving for b yields the level of public debt as

$$b = \frac{g_1 - g_2}{2} + \frac{f_1 - f_2}{2}. \tag{3.23}$$

Knowing that $f_1 = f_2$ and $g_1 < [>] g_2$, results in $b < [>] 0$ whenever $\theta_i > 0$ and $D_1' + \gamma D_2' > [<] D_2'$. This proofs the first claim in Proposition 3.1. The second sentence directly follows from the fact that the social planner used $\theta_i = \theta^* = 1$, such that any politician with $\theta_i \neq 1$ chooses inefficient levels of g_1, g_2 and b due to (3.22). To proof the last statement in Proposition 3.1, consider that conditions (3.5a) and (3.5b) reduce to $u'(g_t) = u'(f_t)$ if $\theta_i = 0$, which implies $g_1 = g_2$. From (3.23), $g_1 = g_2$ and $f_1 = f_2$, it immediately follows that $b = 0$ in this case. ■

3.6.2 Proof of Proposition 3.2

To proof Proposition 3.2, it is expedient to introduce a *preference distance parameter*, $\Delta = (\theta_2 - \theta_1)$, measuring how much preferred internalization rates differ between periods. Since θ_1 is ex-ante known, Δ can be varied by either increasing or decreasing θ_2. Hence, the distance parameter takes values on the interval $\Delta \in [-1, 1]$.

Cramer's rule can be applied to the system of equations

$$G^1 = u'(g_1) - u'(1+b-g_1) - \theta_1\big[D_1'(g_1) + \gamma D_2'(\gamma g_1 + g_2)\big] + \Delta \frac{\partial g_2^v}{g_1} D_2'(\gamma g_1 + g_2) = 0, \tag{3.24a}$$

$$G^2 = u'(g_2) - u'(1-b-g_2) - \theta_1 D_2'(\gamma g_1 + g_2) - \Delta D_2'(\gamma g_1 + g_2) = 0, \tag{3.24b}$$

$$G^b = u'(1+b-g_1) - u'(1-b-g_2) + \Delta \frac{\partial g_2^v}{\partial b} D_2'(\gamma g_1 + g_2) = 0, \tag{3.24c}$$

consisting of first-order conditions (3.10), (3.18) and (3.19) from both periods, in order to obtain the marginal effect

$$\frac{\partial b}{\partial \Delta} = \frac{\partial b}{\partial \theta_2} = \frac{|J_b|}{|J|}, \tag{3.25}$$

according to Cramer's Rule, where J is the Jacobian matrix of cross-derivatives equal to

$$|J| = \det \begin{pmatrix} \partial G^1/\partial g_1 & \partial G^1/\partial g_2 & \partial G^1/\partial b \\ \partial G^2/\partial g_1 & \partial G^2/\partial g_2 & \partial G^2/\partial b \\ \partial G^b/\partial g_1 & \partial G^b/\partial g_2 & \partial G^b/\partial b \end{pmatrix}, \tag{3.26}$$

and J_b is obtained by substituting the column of J containing the cross-derivatives with regard to b, i.e., the third column, with the vector

$$\psi = \Big(- \partial G^1/\partial \theta_2, -\partial G^2/\partial \theta_2, -\partial G^3/\partial \theta_2 \Big)'. \tag{3.27}$$

Employing the quadratic specification of the model, the determinant of the Jacobian can be solved as

$$|J| = \frac{\partial g_2^v}{\partial b}\beta\Big[8\beta(\beta + \theta_2\delta_2) + 2\beta\theta_1\delta_2\Big(1 + \gamma(3\gamma - 2)\Big) + (\theta_2\delta_2)^2\Big(3 + \gamma(3\gamma-2)\Big)\Big] + \frac{\partial g_2^v}{\partial b}\theta_1\delta_1\Big[6\beta(\beta + \theta_2\delta_2) + \delta_2(\beta\theta_1 + 2\theta_2^2\delta_2)\Big], \tag{3.28}$$

which is negative for all possible values of θ_1 and θ_2, considering that $1+\gamma(3\gamma-2) > 0$ for all $\gamma \in [0,1]$. The determinant of J_b in the numerator of (3.25) equals

$$|J_b| = 2D_2'D_2''\frac{\partial g_2^v}{\partial b}\Big(2\beta(1-\gamma) + \theta_1\delta_1\Big)\Delta \tag{3.29}$$

Combining equation (3.29) with $|J| < 0$ and recalling that $D_2', D_2'' > 0$, $\gamma \in (0, 1]$ and $\partial g_2^v / \partial b < 0$, it is straightforward to show that the marginal effect in (3.25) equals zero for $\Delta = 0$, i.e., when the the internalization preference does not change between periods. This represents the certain reelection outcome which is not subject to any strategic incentives. Analogously, $\partial b / \partial \Delta$ is negative [positive] if the second-period government prefers a lower [higher] internalization rate than the incumbent, i.e., for $\Delta <$ [>]0. Hence, b is u-shaped in Δ. This implies that public debt will be lowest under certain reelection and increases as the 'optimal' internalization rate becomes more controversial. ■

3.6.3 Proof of Proposition 3.3

The marginal effect of a change in Δ on g_1 can be derived analogously to the proof of Proposition 3.2 by employing Cramer's Rule to obtain

$$\frac{\partial g_1}{\partial \Delta} = \frac{|J_{g_1}|}{|J|}. \tag{3.30}$$

Recall that $|J| < 0$. Since the numerator of (3.30) is given by

$$|J_{g_1}| = 2\beta D_2' D_2'' \frac{\partial g_2^v}{\partial b} (1 - 3\gamma) \Delta, \tag{3.31}$$

it is immediately apparent that the marginal effect becomes zero for $\Delta = 0$, i.e., in the certain reelection outcome. Furthermore, $\partial g_1 / \partial \Delta$ is positive [negative] if the second-period government prefers a lower [higher] internalization rate than the incumbent, i.e., for $\Delta <$ [>]0 and $\gamma > \tilde{\gamma} = 1/3$. Consequently, the function of g_1 over Δ is *inversely* u-shaped with its maximum in $\Delta = 0$. Hence, the incumbent government provides less of the polluting good, the further apart internalization preferences θ_1 and θ_2 are. In contrast, for $\gamma < \tilde{\gamma}$, g_1 is u-shaped such that provision of the polluting good is lowest under certain reelection and increases with voting uncertainty. This effect occurs regardless of whether the opponent prefers a higher or lower internalization rate than the incumbent government. ■

3.6.4 Proof of Proposition 3.4

To derive Proposition 3.4, first differentiate TD with regard to Δ to obtain

$$\frac{\partial TD}{\partial \Delta} = \left(D_1' + \gamma D_2'\right) \frac{\partial g_1}{\partial \Delta} + D_2' \frac{\partial g_2^v}{\partial \Delta}, \tag{3.32}$$

where $\partial g_1/\partial\Delta$ is already known to be negative if $\theta_1 > \theta_2$ and $\gamma < \tilde{\gamma}$ or $\theta_1 < \theta_2$ and $\gamma > \tilde{\gamma}$ from Proposition 3.3. The marginal effect on second-period provision, $\partial g_2/\partial\Delta$, can be derived by use of Cramer's rule such that its numerator is given as

$$|J_{g_2}| = -D_2'\frac{\partial g_2^v}{\partial b}\Bigg\{\theta_1\delta_1\Big(3\beta + 2\theta_2\delta_2 - \delta_2\frac{\partial g_2^v}{\partial b}\Big) + \Big(\frac{\partial g_2^v}{\partial b}\Big)^2\Big[8\beta(2\beta+\delta_2) + 4\beta(6-\gamma)\theta_2\delta_2 + \theta_2(\delta_2)^2\Big(2+\gamma-2\gamma^2+(6-2\gamma-3\gamma^2)\theta_2\Big) + \frac{1}{\beta}\Big(6\gamma^2\theta_1(\theta_2)^2(\delta_2)^3 + (\theta_2\delta_2)^3\big(2-\gamma-3\gamma^2\big)\Big)\Big]\Bigg\}, \tag{3.33}$$

where all terms in curly brackets are (weakly) positive if $\gamma \in [0,1]$ except for the last term, i.e., $2-\gamma-3\gamma^2 \gtrless 0$. Hence, a sufficient condition for this term to be negative is $\gamma \leq 2/3$. Additionally, the sum in the last line of (3.33) can also be rewritten as

$$(\theta_2\delta_2)^2(2-\gamma-\gamma^2) + 3(\theta_2\gamma\delta_2)^2\delta_2(3\theta_1-\theta_2), \tag{3.34}$$

such that $\theta_1 \geq \theta_2/3$ is another sufficient condition for $|J_{g_2}| > 0$. Together with $|J| < 0$, this implies that $\partial g_2/\partial\Delta$ is always negative for $\Delta < 0$, i.e, $\theta_1 > \theta_2$ and negative for $\Delta > 0$ if $(2-\gamma-3\gamma^2)(\theta_2\delta_2)^3$ is sufficiently large. When both $\partial g_1/\partial\Delta$ and $\partial g_2/\partial\Delta$ are negative for $\Delta <$ [>]0, $\partial TD/\partial\Delta$ is also unambiguously negative which implies that total intertemporal welfare damages from pollution are higher [lower] under voting uncertainty than in the case with certain reelection. ■

3.6.5 Marginal effects of θ_i on b and g_1 under certain reelection

To derive the marginal effects of θ_i on b, I apply Cramer's rule to the system of first-oder conditions (3.5a) to (3.5c) which gives

$$\frac{\partial b}{\partial\theta_i} = \frac{|J_b|}{|J|}, \tag{3.35}$$

where the Jacobian, J, is equivalent to the Hessian matrix, H, associated with the maximization problem under certain reelection. Since the politician optimizes over g_1, g_2, and b, the bordered Hessian has to be negative in the welfare maximum. Hence, it is also known that $|J| < 0$. The numerator, J_b, is obtained by substituting the negative of the cross-derivatives of (3.5a) – (3.5c) with regard to θ_i for the last column in J such that

$$|J_b| = -u''(f)\Big[\Big(D_1' + \gamma D_2' - D_2'\Big)\Big(\theta_i \gamma D_2'' - u''(g_2)\Big) + \Big(D_1' + \gamma D_2'\Big)\Big(\theta_i D_2'' - u''(f)\Big) - D_2'\Big(\theta_i D_1'' + \theta_i \gamma^2 D_2'' - u''(g_1)\Big)\Big]. \tag{3.36}$$

Hence, the direction of the marginal effect equals $\text{sign}(\partial b/\partial \theta_i) = -\text{sign}|J_b|$.

Analogously, the numerator of the marginal effect on g_1

$$\frac{\partial g_1}{\partial \theta_i} = \frac{|J_{g_1}|}{|J|}, \tag{3.37}$$

can be derived as

$$|J_{g_1}| = u''(f)\Big[2u''(g_2)\big(D_1' + \gamma D_2'\big) - 2\theta_i D_2'' D_2' + u''(f)\big(D_1' + \gamma D_2' - D_2'\big)\Big], \tag{3.38}$$

in the general formulation of the model, where the first two terms in square brackets on the RHS are always negative and the last term is negative if the cumulative marginal damage of emissions decreases over time. In this case, $|J_{g_1}|$ is overall positive as the terms in square brackets are multiplied by $u''(f) < 0$. For the quadratic specification, the expression simplifies to

$$|J_{g_1}| = \beta\Big[3\beta D_1' + 2\theta_i \delta_2 D_2' + \beta D_2'(3\gamma - 1)\Big], \tag{3.39}$$

where $\gamma > 1/3$ is a sufficient condition for $|J_{g_1}| > 0$.

Chapter 4

Durable Public Abatement and Optimal Debt under Imperfect Competition

4.1 Introduction[19]

Whether the Paris Agreement – or ambitious environmental policy targets in general – can be reached is contingent on their political feasibility. Especially regarding emission taxation as a means of internalizing pollution externalities, public acceptance is often limited (Umit and Schaffer, 2020). However, research suggests that the majority of voters might actually support even high emission tax rates if revenues are earmarked for funding mitigation and activities that directly benefit citizens, such as public good provision, or for redistribution to households through income tax credits and direct transfers (Beiser-McGrath and Bernauer, 2019; Carattini et al., 2019). This implies that it is not sufficient to just determine the optimal tax rate when considering an emission tax reform. At the same time, fiscal considerations of how and when to spend tax revenues play an integral role for the success of climate policy.

This chapter contributes to the integrated analysis of fiscal and climate policy. Specifically, I focus on the synergies between emission taxation, recycling tax revenues for public abatement and deficit spending in a model with an imperfectly competitive polluting industry. My approach yields three novel results. First, the existing literature suggests that it is optimal to levy an emission tax below the Pigou-

[19] The contents of this chapter are based on M. Kellner (2021) 'Public or Private Abatement? The Impact of Fiscal Policy Constraints' which was previously made available as an *SSRN working paper*.

vian level, i.e., under-internalize, or even subsidize polluting production depending on the degree of firm-side market power. In contrast, I show that over-internalization may occur if tax revenues are not just redistributed in a welfare-neutral way but employed for public spending. Second, as the main result, I find that public abatement funded by the revenues from emission taxation creates a double dividend and, thus, is a welfare-improving substitute for the emission tax and firm-level abatement. On the one hand, abatement reduces environmental damages and the associated welfare loss. On the other hand, it enables the regulator to levy a lower emission tax which attenuates the under-provision problem related to taxing an industry with imperfect competition. Third, I also show that the incentive to substitute public abatement for emission taxation increases in earlier periods when public abatement capital is durable. Hence, in order to fund large early investments, it is optimal to deviate from a balanced budget and issue public debt which will be repaid by future emission tax revenues. These findings imply that recycling emission tax revenues for public abatement is not only associated with a normative welfare gain, but also allows the regulator to levy a lower tax in the optimum which, additionally, improves the feasibility of emission taxation from a political-economy perspective.

To derive these results, I introduce public abatement and an explicit public budget constraint in an established model of emission taxation under imperfect competition. Following Barnett (1980) and Requate (2006), production by a monopolistic firm causes an emission externality which can be reduced by firm-level abatement. Since abatement is costly, there is no incentive to do so unless the government puts a price on emissions. A benevolent government observes the monopolist's decision problem and chooses the welfare-maximizing emission tax. In the existing literature, tax revenues are redistributed to the private sector through lump-sum transfers at constant marginal costs of public funds (MCPF) equal to one. Hence, tax payments and public revenues cancel out in the welfare function. Welfare merely amounts to the total of producer's and consumers' surplus net environmental damages from the pollution externality. In contrast, I assume that the regulator may use emission tax revenues for the provision of a public consumption good or publicly funded emission abatement.[20] By doing so, I expand on the previous literature in several ways.

First, I allow for non-constant MCPF deviating from unity due to collection costs or concave utility from public good provision. As a result, both tax payments and the public budget constraint have to be considered explicitly in the welfare maximization problem. This implies that the optimal emission tax rate depends

[20]Note that the *public consumption good* is assumed to be non-excludable and non-rivalrous, whereas *public abatement* simply indicates that abatement is paid for by the public sector.

not only on the firm's output elasticity with regards to the tax rate, but also on fiscal considerations. Barnett (1980) shows that it is optimal to charge a tax rate below the Pigouvian level or even a negative emission tax rate (i.e., subsidize the monopolist) as positive tax rates exacerbate the under-provision problem associated with imperfect competition. This leads to under-internalization of emissions in the optimum as compared to the first-best scenario. Since I derive that it is optimal to invest in public abatement which is funded by earmarked emission tax revenues, a negative tax rate is no longer feasible in my integrated analysis. Additionally, if the marginal value of the public consumption good is sufficiently high in relation to the market inefficiency and the emission externality, funding objectives can even cause over-internalization of environmental damages as long as the regulator does not engage in public emission abatement.

Second, I consider that the choice of environmental policy instruments is not limited to emission taxation. Instead, as mentioned above, the regulator finds it optimal to always engage in public abatement which recaptures industrial emissions (as long as the abatement technology satisfies the Inada conditions). Since positive investments in public abatement reduce emission and, thereby, the marginal damage, it is optimal to levy a lower tax on emissions when the regulator has the opportunity to invest in public abatement which is funded exclusively by revenues from the emission tax. This has an important implications for welfare in comparison to the emission tax-only policy. While provision of the private good by the monopolist remains inefficiently low, and even below the laissez-faire quantity, output still increases as the emission tax is substituted for by public abatement which also causes a rise in the consumers' surplus and industrial emissions. As the latter effect is absorbed by public abatement, introducing public abatement in favor of lower private abatement leads to a welfare gain compared to the situation where only an emission tax is available. Hence, environmental policy restricted to emission taxation alone is only third-best.

Third, I conduct a two-period analysis acknowledging that investments in public abatement capital may be durable. Since first-period public abatement is still productive in the second period, it is optimal to increase first-period investments. Therefore, following the intuition of my second result, durability creates an additional incentive to lower the emission tax rate in the first period. Consequently, a balanced budget is not desirable in this case. If first-period tax revenues are the only source of funding for first-period investments, the regulator either has to levy an inefficiently high emission tax or spend less than optimal on abatement capital. By issuing debt, second-period revenues from emission taxation can be tapped to the first period to resolve this issue and increase welfare. Hence, my analysis also provides a normative justification for deficit spending.

The last result builds on the assumption that public abatement is durable, whereas private efforts take the form of a pure flow and depreciate entirely at the end of each period. Hence, firm-level abatement represents traditional end-of-pipe technologies, such as industrial filters which have to be replaced regularly. In contrast, by public abatement I refer to measures which sequester emissions that have already been released into the ecosystem. Such investments can include carbon capture and storage (CCS) technologies or afforestation. In a recent study, Bastin et al. (2019) show that afforestation in particular harbors considerable potential for climate change mitigation. If the primary role of forests is to serve as long-term carbon sinks, their commercial utilization is limited because logging, processing and transportation of wood products are associated with emissions (Profft et al., 2009) which, in turn, reduce the effective amount of stored carbon. Hence, afforestation as a durable means of abatement is less attractive for private owners unless the public sector provides financial incentives. In practice, forestry measures represent a non-negligible position in the EU budgetary plan, increasing from EUR 5.4 billion spent between 2007 and 2013 to EUR 8.2 billion[21] for the 2015-2020 planing period (Nègre, 2020). For instance, the Irish government's *Afforestation Grant and Premium Scheme*, which received funding from the EU budget, aims at increasing Ireland's forest-covered area from 11 to 18 percent over a six-year period from 2014 to 2020 (Department of Agriculture, 2015). According to McCarthy et al. (2003), public upfront payments to planters proved the most cost-effective instrument of public abatement in this case. While this makes a strong case to include public abatement in general, the productive lifetime of forests clearly exceeds the durability of industrial filters. Thus, for tractability, I make the simplifying assumption that only the public sector invest in durable abatement technologies.

The literature on public incentives for firm-level abatement is founded on the early models by Downing and White (1986) and Milliman et al. (1989). Recent work on this topic is largely inspired by Requate and Unold (2001,2003) and has focused on technology adoption in asymmetric settings, e.g., compliance with emission regulation (Arguedas et al., 2010) or imperfect information on firms' adaptation costs (D'Amato and Dijkstra, 2015). Requate (2006) provides an extensive review of different approaches to modeling firm abatement, market structures and policy

[21] For the 2015-2020 period, 63 percent of this budget are allocated to afforestation and damage prevention, e.g., improving wildfire and drought resilience of existing forests (Nègre, 2020) which also affects their future capabilities to absorb carbon emissions.

instruments. While many of these contributions examine the effect of public incentives on the adoption of less-polluting technologies by firms, the focus of my analysis is rather on the role of public abatement which, to the best of my knowledge, has previously been ignored in this context. By considering the effect of market power on abatement incentives, the paper by Barnett (1980) is relevant to my model, as well as Benchekroun and Van Long (1998), who derive the optimal tax path over time in an oligopoly with stock pollution. However, fiscal constraints are of no concern in any of these contributions with the exception of Bayindir-Upmann (2000), who shows that a distortive capital tax can be reduced if the regulator taxes emissions, alluding to the *double-dividend* hypothesis. Additionally, the interrelation between taxation and climate policies has been addressed recently by Barrage (2020) who emphasizes the effects of emission taxation on second-best capital levies and computes a dynamic general equilibrium model. Yet, none of the above mentioned papers incorporates public abatement. The closest in this regard might be the analysis by Fischer (2008), who assumes that the regulator does not directly engage in abatement, but invests in research which improves the efficiency of private abatement.

In the following section, I first outline the profit maximization problem of the monopolistic firm as well as the regulator's welfare optimization objective. In Section 4.3, I investigate the role of public abatement and introduce an explicit public budget constraint in the static model familiar from the existing literature to derive the central findings of this chapter. In Section 4.4, I examine how durable public abatement capital affects these results under a balanced budget rule, before turning to the welfare gains associated with deficit spending in Section 4.5. The chapter concludes with a numerical analysis in Section 4.6 followed by a summary and a discussion of the results.

4.2 Model

The model outlined below closely follows the basic framework established by Barnett (1980) and Requate (2006). In addition to the assumptions of this basic framework, I introduce an option for the regulator to invest in (durable) public abatement capital and spend tax revenues on a public consumption good. In general, I consider a two-period model, where $t = 1, 2$ is the time index. When abatement capital is non.durable and depreciates entirely at the end of each period, I focus on a one-period model and drop the time index t.

4.2.1 Private firm's decision

In each period t, a monopolistic firm produces the quantity q_t of consumer good Q, facing the inverse demand function $P(q_t)$ with $P'(q_t) < 0$. Production is associated with emissions e_t which can be abated at the expense of higher production costs. The firm's production costs, $C(q_t, e_t)$, are a convex and increasing function in output, q_t, i.e., $C_q > 0$ and $C_{qq} > 0$. The threshold e^{max} denotes the case where the firm does not abate any emissions such that $C_e(q_t, e^{max}) = 0$. Below the threshold, emission abatement increases production costs at increasing rates, i.e., $C_e < 0$ and $C_{ee} > 0$ for all $e_t < e^{max}$. Since the firm has no incentive to produce more emissions than caused by the unabated production process and, additionally, the regulator levies a positive emission tax, τ_t, the optimal level of emissions, will always be below e^{max}. The cross-derivative of the cost function, C_{qe}, is assumed to be negative meaning that abatement increases the marginal cost of any given quantity q.

The monopolist maximizes the present value of profits

$$\pi = \sum_t \left\{P(q_t)q_t - C(q_t, e_t) - \tau_t e_t\right\}, \tag{4.1}$$

where the discount rate has been normalized to zero. The first-order conditions with respect to q_t and e_t in $t = 1, 2$ read

$$\frac{\partial \pi}{\partial q_t} = P(q_t) + P'(q_t)q_t - C_q(q_t, e_t) = R'_M(q_t) - C_q(q_t, e_t) = 0, \tag{4.2}$$

$$\frac{\partial \pi}{\partial e_t} = -C_e(q_t, e_t) - \tau_t = 0, \tag{4.3}$$

where $R_M(q_t) = P(q_t)q_t$ and $R'_M(q_t) = P(q_t)+P'(q_t)q_t$. According to (4.2) and (4.3), the optimal quantities and emissions in each period can be implicitly expressed as functions of the emission tax rate, $q_t = q(\tau_t)$ and $e_t = e(\tau_t)$. Applying the Implicit Function Theorem to equations (4.2) and (4.3) gives the marginal effects of an increase in the emission tax rate on firm decisions as

$$\frac{\partial q_t}{\partial \tau_t} = \frac{C_{qe}(q_t, e_t)}{|H_t|} < 0 \quad \text{and} \quad \frac{\partial e_t}{\partial \tau_t} = \frac{R''_M(q_t) - C_{qq}(q_t, e_t)}{|H_t|} < 0, \tag{4.4}$$

where $R''_M(q_t) - C_{qq}(q_t, e_t)$ is the second-order condition with regard to q_t and, thereby, necessarily negative to ensure a profit maximum. Furthermore,

$$|H_t| = \left[R''_M(q_t) - C_{qq}(q_t, e_t)\right]\left[-C_{ee}(q_t, e_t)\right] - \left[C_{qe}(q_t, e_t)\right]^2 > 0, \tag{4.5}$$

is the determinant of the firm's Hessian in period t which has to be positive in the profit maximum. As a result, $q(\tau_t)$ and $e(\tau_t)$ are unambiguously decreasing in the emission tax rate. Thus, the monopolist reduces both emissions and output, as the tax rate increases. Thus, a positive emission tax exacerbates under-provision of the private good which is already inherent to the imperfectly competitive industry.

4.2.2 Regulator's problem

The regulator's objective is to maximize social welfare, W, which amounts to the total of producer's and consumers' surplus in addition to the utility from public good provision net environmental damages. While utility from provision of the public good, G, in period t, g_t, equals $V(g_t)$ with $V'(g_t) > 0$ and $V''(g_t) \leq 0$, damages caused by the pollution externality are denoted by $D_t[e_t - \varphi(A_t)]$ with $D_t[\cdot]' > 0$ and $D_t[\cdot]'' \geq 0$. The central innovation in my model is the regulator's ability to spend tax revenues not only on provision of the public good, g_t, but also on abatement investments, a_t, which contribute to a stock of public abatement capital according to $A_1 = a_1$ and $A_2 = a_2 + (1 - \delta)a_1$. Hence, $\delta > 0$ denotes the depreciation rate of public abatement capital.[22] The abatement technology, $\varphi(A_t)$, reduces environmental damages by recapturing emissions caused by production in the private sector at a decreasing rate, i.e., $\varphi' > 0$ and $\varphi'' \leq 0$. Hence, welfare in each period, W_t, is given by

$$W_t = \int_0^{q(\tau_t)} P(z)dz - C\big[q(\tau_t), e(\tau_t)\big] - \tau_t e(\tau_t) + V(g_t) - D\big[e(\tau_t) - \varphi(A_t)\big]. \tag{4.6}$$

The regulator maximizes the sum of intertemporal welfare, i.e., $W_1 + W_2$, considering the per-period budget constraints

$$\tau_t e(\tau_t) = a_t + g_t, \quad \text{for} \quad t = 1, 2. \tag{4.7}$$

By implicitly defining $V(g_t)$ such that $V'(g_t) \equiv 1$ and $V''(g_t) \equiv 0$ and ignoring public abatement ($a_t \equiv 0$), the vast majority of contributions to the literature on public incentives for firm-level abatement assumes that tax revenues are redistributed as a welfare-neutral lump-sum transfer, such that public revenues (i.e., the firm's tax burden) and public spending cancel out in the social welfare function.

[22] In the case of afforestation, even negative depreciation rates could be considered as a tree's growth rate (and, thereby, its carbon absorption capacity) generally seems to increase with age (Stephenson et al., 2014). For simplicity, I focus only on positive depreciation rates in this analysis.

Notable exceptions to this are Ebert (2007), who acknowledges distributional preferences, i.e., non-neutral public transfers, as well as Laffont and Tirole (1996) and Bayindir-Upmann (2000) who assume $V'(g_t) \equiv \lambda$ with $\lambda > 1$ but also neglect public abatement. The parameter λ can either be interpreted as the constant marginal utility of public good provision or, alternatively, as the marginal cost of public funds (MCPF). Thus, these authors consider revenue raising objectives in the analysis of emission taxes. If the MCPF is larger than one, a unit of public revenues is more valuable than one unit of private income, e.g., due to collection costs. Therefore, the regulator has an additional incentive to increase revenues from the emission tax. As will be shown in Section 4.5, a constant MCPF represents a rather special case which may be too simplistic in the two-period model. Still, in order to compare my findings to the benchmark scenario in Barnett (1980) and Requate (2006), I will also examine the case with a constant parameter λ next to the more complex model with decreasing marginal utility from public good provision, i.e. $V'(g_t) > 0$ and $V''(g_t) < 0$.

It will be expedient to express public revenues as $R(\tau_t) = \tau_t e(\tau_t)$ which is also commonly referred to as the Laffer curve. I impose the fairly general assumption that the Laffer curve is inversely u-shaped.

Assumption A4.1 *The Laffer curve is twice continuously differentiable and satisfies $R'(\tau_t) = e(\tau_t) + \tau_t e'(\tau_t) \gtreqless 0$ if and only if $\tau_t \lesseqgtr \bar{\tau}$ with $\bar{\tau} > 0$, $R''(\tau_t) = 2e'(\tau_t) + \tau_t e''(\tau_t) < 0$ and $R(0) = 0$.*

By Assumption A4.1, an increase of the tax rate will yield higher public revenues up to $\bar{\tau}$. If the tax rate increases beyond the threshold $\bar{\tau}$, the monopolist will substitute abatement for emissions so intensively that a higher tax rate entails lower public revenues. For purely revenue-raising, distortionary taxes, it is usually the case that the optimal tax rate, τ^d, is located on the increasing side of the Laffer curve and, thus, satisfies $R'(\tau^d) > 0$. In contrast, a first-best emission tax rate, with the sole objective of internalizing the pollution externality, will be at the Pigouvian level, i.e., equal to the marginal environmental damage. Hence, it is generally not possible to rule out optimal tax rates on the decreasing side of the Laffer curve in general. Nonetheless, I assume $R'(\tau^e) > 0$ in the subsequent analysis if not explicitly stated otherwise, because the second-best emission tax rate in my model is influenced by two additional effects which favor low tax rates or tax rates on the increasing side of the Laffer curve, respectively. On the one hand, imperfect competition leads to under-provision of the private good even before the regulator levies a tax on emissions. Taxation further aggravates this market failure which implies that the trade-off between production efficiency and emission internalization leads to tax rates below the Pigouvian level (see Barnett, 1980; Requate, 2006). On the other hand, the regulator's revenue raising objective additionally favors tax rates on the increasing side of the Laffer curve. Thus, while I cannot rule out tax rates with $R'(\tau_t) < 0$, I focus on the case with $R'(\tau_t) > 0$ for tractability reasons.

4.3 Public abatement in the one-period model

In order to establish how introducing public abatement affects the single-period benchmark scenario from the existing literature, I first examine the case with non-durable public abatement ($\delta = 1$). Hence, the regulator's optimization problem can be decomposed into independent per-period maximizations of W_1 and W_2 as given by (4.6) under the respective per-period budget constraints in (4.7). Therefore, it is possible to neglect the time index t in this section and focus on a single period for simplicity. By rearranging (4.7) for $g = \tau e(\tau) - a$ and substituting in (4.6) and considering the monopolist's optimal reactions, $q(\tau)$ and $e(\tau)$, as derived in Section 4.2.1, the regulator's first-order conditions follow as

$$\frac{\partial W}{\partial a} = -V'(g_t) + \varphi'(a)D'\big[e(\tau) - \varphi(a)\big] = 0, \tag{4.8}$$

$$\begin{aligned}\frac{\partial W}{\partial \tau} = \Big(P\big[q(\tau)\big] - C_q\Big)q'(\tau) - C_e e' + \big[V'(g_t) - 1\big]\big[e(\tau) + \tau e'(\tau)\big] \\ - D'\big[e(\tau) - \varphi(a)\big]e'(\tau) = 0.\end{aligned} \tag{4.9}$$

In order to obtain an interior solution, as implicitly assumed by the system of first-order conditions above, public abatement has to be sufficiently productive in comparison to the alternative of providing the public good g. This is ensured if the public abatement technology fulfills the Inada conditions, specifically, if $\lim_{a\to 0} \varphi'(a) = \infty$.

By substituting $P(q_t) - C_q = -P'(q_t)q_t$ and $C_e + \tau_t = 0$ from (4.2) and (4.3), respectively, and further employing $\varepsilon_q = P(q)/P'(q)q < 0$ in (4.9), I obtain

$$\tau = D'\big[e(\tau) - \varphi(a)\big] + \frac{P\big[q(\tau)\big]}{\varepsilon_q}\frac{q'(\tau)}{e'(\tau)} - \big[V'(g_t) - 1\big]\frac{R'(\tau)}{e'(\tau)}, \tag{4.10}$$

where ε_q is the price elasticity of demand for the private good. For $V'(g_t) \equiv \lambda = 1$, the third term on the RHS of (4.10) cancels out and the expression coincides with the (implicit) optimal tax rate derived by Requate (2006). Hence, it can be interpreted analogously. The first term on the RHS is positive as higher tax rates increase the cost of emitting and, thereby, reduce the welfare loss from pollution. Yet, since I allow for public abatement, this incentive to levy a positive tax rate is decreasing in a. Considering that the price elasticity of demand is always negative ($\varepsilon_q < 0$), the second term in (4.10) is negative. Due to this term, the optimal tax rate falls short of the Pigouvian level in order to account for the monopolist's incentive to under-provide the private good even in the absence of emission taxation. In principle, the optimal tax rate could even become negative if the market inefficiency due to imperfect competition outweighs the environmental externality.[23] However, negative tax rates would require an additional source of public funding or the option to sell instead of provide g. This case is easily ruled out by assuming that public good provision is sufficiently valuable, e.g., $V''(g) \to \infty$ for $g \to 0$. The second new effect in my model is captured by the third term in (4.10). It represents the revenue-raising incentive for all $V'(g_t) > 1$ and can take two different roles. For tax rates on the decreasing side of the Laffer curve ($R'(\tau) < 0$), revenue raising mandates a lower tax rate, amplifying the effect of the market inefficiency term. In contrast, if the tax rate is located on the increasing side of the Laffer curve ($R'(\tau) > 0$), an additional increase in τ generates more public revenues which can (at least partially) offset the under-internalization incentive stemming from the second term. This results in an emissions level closer to the first-best outcome than when revenue-raising incentives are neglected. Moreover, the funding objective represented by the third term may even lead to over-internalization, i.e., an emission tax rate above the Pigouvian level. This case can only occur when pollution damages are low enough for the tax rate to be on the increasing side of the Laffer curve. Otherwise, an over-internalizing tax rate would generate lower revenues which does not conform with the funding objective.

In the next step, I compare the optimal policy when only an emission tax is available to the scenario where the regulator is also able to invest in public abatement. From first-order conditions (4.8) and (4.9), I prove the following result in Appendix 4.8.1:

Proposition 4.1 *When a public abatement technology is available, it is optimal to invest in public abatement financed by the emission tax and levy a lower tax rate than in the status quo without public abatement. This result always holds under constant MCPF, i.e.,* $V'(g) \equiv \lambda$. *For decreasing marginal utility, i.e.,* $V'(g) > 0$ *and*

[23] As shown by Barnett (1980), the regulator can at best achieve a second-best solution. In order to reach the first-best outcome, an additional instrument, e.g., an output subsidy, would be required. While direct output subsidies are often infeasible, e.g., due to EU competition laws, Gersbach and Requate (2004) show how a tax-refund system can be adjusted to also restore the first-best solution in an oligopoly market.

$V''(g) < 0$, *the same effect occurs under the sufficient condition that* $\varphi' e' D'' < V'' R'$.

Proposition 4.1 leads to a striking result. Even though investing in public abatement capital is costly, the regulator cuts the emission tax rate when compared to the literature benchmark where taxation is the only available policy instrument.[24] Thus, if the tax rate was initially on the increasing side of the Laffer curve, it becomes optimal to accept a decrease in public revenues. Hence, public abatement requires a decrease in public good provision larger than the cost of public abatement. While this finding may seem counterintuitive at first, it is caused by the threefold role of emission taxation. Its fundamental motivation is to increase the price of emissions and internalize pollution damages. Second, the tax also provides funds for spending on a public good and investment in public abatement capital. These two effects increase welfare in the tax rate (as long as $R'(\tau) > 0$). However, a positive emission tax also distorts production of the private good. By introducing public abatement, the regulator can maintain the same marginal damage from emissions at a lower tax rate. This alleviates the inefficiency due to imperfect competition and increases the available quantity of the private good but also emissions caused by the monopolist. Hence, by (partially) substituting public for private abatement, the regulator can achieve welfare gains. Disregarding distributional objectives, a policy mix of public abatement investments and public good provision is always preferable to a system refunding all revenues from the emission tax as a lump-sum transfer.

In the discussion of (4.10), I argue that the revenue-raising incentive captured by the third term can lead to over-internalization if the marginal value of public good provision is sufficiently large. The first term in (4.10) reveals that positive public abatement decreases the marginal damage of emissions for ceteris-paribus constant tax rate. Yet, since public abatement spending also mandates lower tax rates according to Proposition 4.1, it is not clear whether the marginal damage and, thus, the Pigouvian tax rate, increases or decreases in total when the regulator engages in public abatement. Hence, over-taxation may still occur in the presence of public abatement but will be attenuated by the tax-decreasing effect of a.

In a sense, the economy earns a *double dividend* from public abatement. This term deliberately alludes to the seminal double-dividend hypothesis which, essentially, suggests that revenue-raising environmental taxes might not only reduce emis-

[24] Intuitively, for tax rates on the decreasing side of the Laffer curve ($R'(\tau) < 0$), introducing a will also lead to a lower tax rate as the only benefit from further increasing τ is a reduction of emission damages which could also be achieved by investing in public abatement. In contrast, substituting emission taxation for public abatement not only improves provision of the private good but also generates higher tax revenues which can be spent on g and a.

sions but could also enable the regulator to cut other, purely distortive taxes (see Schöb, 2005, for an overview). Although I do not consider alternative sources of public funding, public abatement has similar properties in this model. Due to imperfect competition in the market for the private consumption good, the emission tax itself is the source of an additional distortion. Public abatement attains the same objective as the emission tax (i.e., lower pollution damages) while avoiding its distortionary effect on provision of the private good.

4.4 Durable public abatement capital

When public abatement efforts include investments in water treatment facilities, carbon capture and storage (CCS) or afforestation, it seems reasonable to also consider the case where public abatement capital is durable, i.e., $0 < \delta < 1$. Therefore, individual periods can no longer be examined in isolation as investments from the first period affect the stock of abatement capital in the second period. The regulator now solves the intertemporal optimization problem

$$W = \sum_t \Big\{ \int_0^{q(\tau_t)} P(z)dz - C\big[q(\tau_t), e(\tau_t)\big] - \tau_t e(\tau_t) + V(g_t) \Big\} \\ - D\big[e(\tau_1) - \varphi(a_1)\big] - D\big[e(\tau_2) - \varphi\big(a_2 + (1-\delta)a_1\big)\big]. \tag{4.11}$$

After substituting for g_t as above, the regulator maximizes over τ_t and a_t for all $t = 1, 2$ at the beginning of the first period. The first-order conditions then read

$$W_{\tau_1} = -P'\big[q(\tau_1)\big]q(\tau_1)q'(\tau_1) - e(\tau_1) + V'\big[R(\tau_1) - a_1\big]R'(\tau_1) - D_1'e'(\tau_1) = 0, \tag{4.12}$$

$$W_{\tau_2} = -P'\big[q(\tau_2)\big]q(\tau_2)q'(\tau_2) - e(\tau_2) + V'\big[R(\tau_2) - a_2\big]R'(\tau_2) - D_2'e'(\tau_2) = 0, \tag{4.13}$$

$$W_{a_1} = -V'\big[R(\tau_1) - a_1\big] + \varphi'(a_1)D_1' + (1-\delta)\varphi'\big[a_2 + (1-\delta)a_1\big]D_2' = 0, \tag{4.14}$$

$$W_{a_2} = -V'\big[R(\tau_2) - a_2\big] + \varphi'\big[a_2 + (1-\delta)a_1\big]D_2' = 0, \tag{4.15}$$

with $D_1' = D'[e(\tau_1) - \varphi(a_1)]$ and $D_2' = D'[e(\tau_2) - \varphi(a_2 + (1-\delta)a_1)]$, respectively. The first two terms in (4.12) and (4.13) have already been substituted from the monopolist's optimality conditions (4.2) and (4.3), respectively. In Appendix 4.8.2, the following results are proved in the neighborhood of $\delta = 1$ for tractability:

Proposition 4.2 *When public abatement capital becomes more durable (δ decreases) in the neighborhood of $\delta = 1$, it is optimal to*

(i) invest more in public abatement capital, a_1, in the first period,

(ii) and levy a lower first-period emission tax rate, τ_1, while keeping the second-period tax rate, τ_2, constant in case of constant MCPF, i.e., $V'(g) \equiv \lambda$, or

(iii) levy a lower [higher] first-period emission tax rate, τ_1, while cutting the second period tax rate, τ_2, in case of decreasing marginal utility, i.e., $V'(g_t) > 0$ and $V''(g_t) < 0$ if $R'(\tau_t) > 0$ and $\varphi' e' D'' < [>] V'' R'$.

Proposition 4.2 is derived in the neighborhood of $\delta = 1$ because, otherwise, it is not possible to determine unique signs for the cross-derivatives of first-order conditions (4.12) to (4.15). Indeed, as the depreciation rate decreases further, the effects observed above can change as I will show numerically in Section 4.6. Nonetheless, Proposition 4.2 reveals some intuition about how optimal policy is affected by durability if the depreciation rate remains sufficiently high. The first part confirms the intuition that an increase in durability induces the regulator to invest more in public abatement capital in the first period. This result is not contingent on the specification of $V''(g_t)$.

In principle, the effect of durability gains on public abatement spending described in part (i) of Proposition 4.2 creates incentives similar to Proposition 4.1. As first-period investments in public abatement capital rise, the regulator could lower the emission tax rate without risking higher pollution damages. This intuition is conformed by part (ii) of Proposition 4.2 for a constant marginal utility of g_t (or a constant MCPF, respectively). If τ_1 is on the increasing side of the Laffer curve, a tax cut is associated with lower first-period revenues which implies that g_1 has to decrease in order to keep the public budget balanced. Hence, spending on the public good in the first period, g_1, merely acts as a reserve for higher public abatement investments, a_1, in response to durability gains.

However, as revealed by part (iii), this result is contingent on the simplifying assumption of a constant MCPF as standard in the literature. In contrast, when analyzing the specification with a concave utility function, $V(g_t)$, this is only true for tax rates on the increasing side of the Laffer curve if $-V''(g_1)$ is sufficiently low.[25] Then, it is still optimal to forfeit spending on g_1 in favor of higher abatement investments and a lower tax rate. While a decrease in first-period provision of the

[25] For tax rates on the decreasing side of the Laffer curve, τ_1 always decreases in durability gains as $R'(\tau_1) < 0$ implies that $W_{\tau a} < 0$ regardless of the size of $V''(g_1) \leq 0$. However, in this case, the effect on τ_2 is no longer analytically unambiguous.

public good leads to a higher marginal value of g_1, increasing the marginal value of tax revenues, this effect is still outweighed by the efficiency gain associated with a lower tax rate. Yet, if $-V''(g_1)$ becomes sufficiently large, the marginal value of public good provision increases so fast when cutting g_1 that the regulator cannot afford lower tax rates and, instead has to increase revenues by raising τ_1. In the second period, durability gains in the neighborhood of $\delta = 1$ always lead to a tax cut when the marginal utility from g_t is strictly decreasing.

There are two main findings to be taken from this section. First, welfare gains are possible by increasing first-period investments, a_1, if public abatement capital becomes durable, even if this requires a higher tax rate, τ_1, or lower spending on the public good, g_1. Second, the findings with regard to the optimal emission tax rates can differ considerably depending on whether one assumes constant or decreasing MCPF. Hence, the standard assumption of constant MCPF may no longer be tenable in the two-period model with durability.

4.5 Welfare effect of public debt

As in the case of part (iii) of Proposition 4.2, it may be necessary to increase first-period taxation to fund higher investments in durable public abatement capital even though public abatement was shown to be a substitute for emission taxation. This result is driven by implicitly imposing a balanced budget rule in the previous section. Therefore, I examine how these findings are affected if first-period spending can be debt funded. The budget constraints for the first and second period, respectively, are then given by

$$a_1 + g_1 = R(\tau_1) + b \qquad \text{and} \qquad a_2 + g_2 = R(\tau_2) - b, \tag{4.16}$$

where b denotes the value of bonds issued by the small open economy on the international capital market. The government is committed to fully service its debt maturing at the beginning of the second period. In order to clearly discern debt incentives due to durability from general time preferences, the interest rate is set to zero and the regulator does not discount future utility.

The regulator still maximizes the objective function (4.11) where g_1 and g_2 are now substituted for by solving the respective budget constraint in (4.16). Thus, the additional first-order condition with regard to b now equals

$$\frac{\partial W}{\partial b} = V'\big[R(\tau_1) + b - a_1\big] - V'\big[R(\tau_2) - b - a_2\big] = 0. \tag{4.17}$$

By substituting $V'(g_t) \equiv \lambda$ in (4.17), it becomes immediately apparent that this condition is fulfilled for any feasible level of public debt under the assumption of constant MCPF. Therefore, lifting the balanced budget requirement form the previous section would not affect welfare if the regulator does not want to spend more on abatement in period t than earned from tax revenues in the same period, i.e., as long as $a_t < R(\tau_t)$.

In the case with decreasing marginal utility from g_t, however, (4.17) requires that public debt is employed to ensure a constant provision of the public good, i.e., $g_1 = g_2 \equiv g$. By solving for b, the two per-period budget constraints in (4.16) can be rearranged as the single intertemporal constraint

$$g_1 + g_2 + a_1 + a_2 = R(\tau_1) + R(\tau_2). \tag{4.18}$$

Given constant provision of the public good, this may be solved for g as

$$g = \frac{1}{2}\big[R(\tau_1) + R(\tau_2) - a_1 - a_2\big]. \tag{4.19}$$

Now, substituting for g allows to express the regulator's welfare maximization problem as a function of only abatement efforts and the tax rates, resulting in

$$\begin{aligned} W = \sum_t \Bigg\{ \int_0^{q(\tau_t)} & P(z)dz - C\big[q(\tau_t), e(\tau_t)\big] - R(\tau_t) \\ & + V\left(\frac{1}{2}\big[R(\tau_1) + R(\tau_2) - a_1 - a_2\big]\right) \Bigg\} \\ & - D\big[e(\tau_1) - \varphi(a_1)\big] - D\big[e(\tau_2) - \varphi\big(a_2 + (1-\delta)a_1\big)\big]. \end{aligned} \tag{4.20}$$

Differentiating with respect to the tax rates and investments in public abatement capital, I prove the following result in Appendix 4.8.3:

Proposition 4.3 *When public abatement capital becomes more durable (δ decreases) in the neighborhood of $\delta = 1$ and the regulator is able to issue public debt, it is optimal to*

(i) invest more in public abatement capital, a_1, in the first period and reduce second-period abatement efforts, a_2,

(ii) cut the first-period emission tax rate, τ_1, while levying a higher tax rate, τ_2 in the second period and

(iii) issue a positive amount of public debt, $b > 0$,

if $V''(g_t) < 0$, $R'(\tau_t) > 0$, $\varphi' e' D'' < \frac{1}{2} V'' R'$ *and* $W_{\tau_2 \delta}$ *is sufficiently small.*

Proposition 4.3 shows that a benevolent planner should issue public debt in order to fund higher investments in the first period if public abatement capital becomes durable. This finding also implies that the effect on emission taxation in the second period fundamentally differs from Proposition 4.2. While the regulator would levy a lower [constant] second-period tax rate, τ_2, in case of decreasing [constant] MCPF under a balanced budget rule, the opposite becomes optimal when it is possible to issue debt. In other words, the regulator does not just transfer the savings from lower abatement efforts, a_2, to the first period but raises additional revenues in order to fund even larger deficit spending on a_1 and g_1. Since $W_{\tau_t a_t}$ in (4.46) is always smaller than $W_{\tau a}$ in (4.40) for $\delta = 1$, it can be optimal to lower the first-period tax rate, τ_1, if debt accumulation is possible while τ_1 would have to increase under a balanced budget rule. Issuing debt drives a wedge between the first and second-period tax rates which initially increases as public abatement becomes more durable. However, in Appendix 4.8.4, I derive that, if public abatement capital is perfectly durable ($\delta = 0$), the tax rates are constant across periods again implying that at least one tax rate has to be (inversely) u-shaped in δ. Thus, the wedge between the tax rates is largest in some $0 < \tilde{\delta} < 1$, increasing as durability improves [falls] if the initial depreciation rate is located between $\tilde{\delta}$ and 1 [0 and $\tilde{\delta}$].

4.6 Numerical analysis

Since the analytical analysis above can only provide unambiguous results for depreciation rates sufficiently close to one, I also conduct a numerical analysis. This does not only illustrate the previous findings but sheds additional light on the dynamics if public abatement capital is relatively durable.

First, I assume pollution damages to follow a quadratic function of unabated emissions from production of the private good and public abatement efforts

$$D\big[e(\tau_t), A_t\big] = \frac{d}{2}\Big[e(\tau_t) - \theta\sqrt{A_t}\Big]^2. \tag{4.21}$$

Equation (4.21) implicitly specifies the public abatement technology as $\varphi(A_t) = \theta\sqrt{A_t}$ such that $\theta \geq 0$ acts as a productivity parameter. In the case of decreasing MCPF, the utility from provision of the public good is assumed to equal

$$V(g_t) = \sqrt{g_t}. \tag{4.22}$$

Suppose that the monopolist faces the inverse demand function

$$P(q_t) = \alpha - \beta q_t, \tag{4.23}$$

with $\alpha, \beta > 0$. Production costs are given by

$$C(q_t, e_t) = c^q q_t + \frac{c^a}{2}(q_t - e_t)^2, \tag{4.24}$$

where $c^q > 0$ and $c^a > 0$ denote production and abatement cost parameters. Then, solving the firm's profit maximization problem yields the optimal quantity of the private good and firm-level abatement as reaction functions

$$q(\tau_t) = \frac{\alpha - c^q - \tau_t}{2\beta} \qquad \text{and} \qquad e(\tau_t) = \frac{\alpha - c^q}{2\beta} - \frac{2\beta + c^a}{2\beta c^a}\tau_t. \tag{4.25}$$

From the reaction function $e(\tau_t)$, the slope of the Laffer curve can be derived as

$$R'(\tau_t) = \frac{\alpha - c^q}{2\beta} - \frac{2\beta + c^a}{\beta c^a}\tau_t \gtrless 0. \tag{4.26}$$

Numerical results are computed for the parameter specification $\alpha = 10$, $\beta = 1$, $c_q = 0.5$, $c_a = 1$, $d = 1$, $\theta = 0.2$ acknowledging that the public abatement technology may be relatively costly or less productive than firm-level abatement. The high value for α is chosen in order to magnify the results and increase visual accessibility.

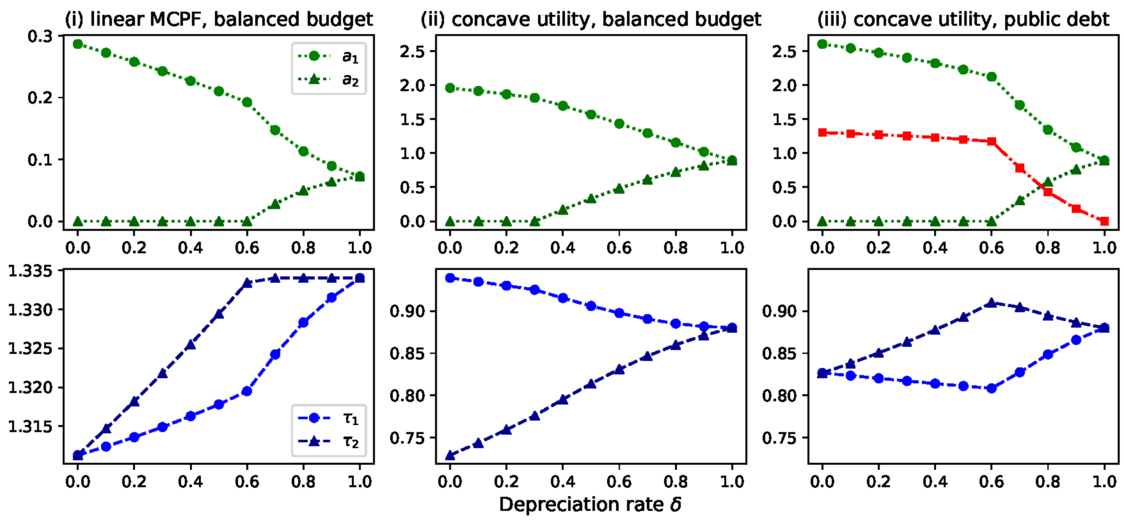

Figure 4.1: Welfare-maximizing outcomes for various policy regimes and depreciation rates

Figure 4.1 depicts the optimal choice of tax rates and public abatement efforts in each period for depreciation rates on the interval $\delta \in [0, 1]$ and linear utility with $\lambda = 1$ from public good provision in panel (i). If the regulator cannot issue debt and utility from the public good is linear, it is optimal to keep second period taxation constant for depreciation rates between 0.6 and 1 while levying a lower tax in the first period. This confirms part (ii) of Proposition 4.2 in the numerical example. For depreciation rates below 0.6, τ_2 decreases at a faster rate than τ_1 such that the tax rates are at the same level again when the depreciation rate reaches $\delta = 0$. It is due to note, that the tax rates only coincide in this point if the 'reserves' which can be tapped by reducing g_1 in order to increase a_1 are sufficiently large. Otherwise, if the marginal productivity of a_1 is larger than λ even in $a_1 = R(\tau_1)$, the regulator chooses $\tau_1 > \tau_2$ to increase tax collection.

Panel (ii) in Figure 4.1 depicts the case with a concave utility function, $V(g_t)$, under a balanced budget rule. It is optimal to continuously increase first-period taxation and collect lower taxes in the second period as durability improves. Hence, the parameters specified above represent part (iii) of Proposition 4.2, where $-V''(g_1)$ is sufficiently high such that equation (4.40) is positive. For low depreciation rates, the regulator sets $a_2 = 0$, spending the entirety of second-period revenues on provision of the public good, g_2. Abatement efforts, a_1, increase considerably faster than first-period tax revenues. Thus, under the balanced budget rule, provision of the public good will be lower in the first than in the second period for all $\delta < 1$.

As derived in the previous section, this cannot be optimal if the government is able to maintain a budget deficit at the end of the first period. Instead, the regulator chooses $g_1 = g_2$. The third panel in Figure 4.1 shows that, with increasing durability, the regulator issues debt to invest even more in the stock of public abatement capital in the first period than if public debt is exogenously fixed at zero. In contrast to the solution under a balanced budget rule, the first-[second-]period tax rate now decreases [increases] as durability improves in the neighborhood of $\delta = 1$. Tax rates are [inversely] u-shaped such that they coincide not only in the full depreciation setting but also in $\delta = 0$. This minimizes distortions in the private good market. Comparing the individual panels in Figure 4.1, this is only possible if either transfers to households can be tapped as a source of 'reserve' funds under constant MCPF as in (i) or if funds can be shifted between periods via public debt as in (iii).

Table 4.1 provides a selection of numerical results for various policy regimes. Case A represents the welfare optimum if the regulator cannot invest in public abatement and tax revenues are exclusively spent on provision of the public good. This solution generates the lowest level of welfare and represents the benchmark

Table 4.1: Numerical solutions for various policy regimes and depreciation rates

	Case A (no abatement)	Case B ($\delta = 1$) (full depreciation)	Case C ($\delta = 0.7$) (balanced budget)	Case D ($\delta = 0.7$) (public debt)
W	48.2307	48.9144	49.0239	49.0436
τ_1	0.99	0.8801	0.8905	0.8275
τ_2	0.99	0.8801	0.8466	0.9045
a_1	–	0.8930	1.2941	1.7053
a_2	–	0.8930	0.6149	0.3060
g_1	3.2324	2.1256	1.7462	1.9807
g_2	3.2324	2.1256	2.3313	1.9807
b	0	0	–	0.7824
$R(\tau_1)$	3.2324	3.0186	3.0403	2.9036
$R(\tau_2)$	3.2324	3.0186	2.9462	3.0692
$R'(\tau_1)$	1.7799	2.1097	2.0786	2.2674
$R'(\tau_2)$	1.7799	2.1097	2.2102	2.0365
D_1	5.33	5.2516	5.0778	5.2732
D_2	5.33	5.2516	5.3785	5.1598

Note: Numerical results for the model specified by (4.21), (4.23) and (4.24) with parameters $\{\alpha, \beta, c_q, c_a, d, \theta\} = \{10, 1, 0.5, 1, 1, 0.2\}$ and δ as given in each column.

scenario from the existing literature.[26] Welfare increases if the regulator also funds non-durable abatement efforts in addition to providing the public good as apparent from comparing the outcome to Case B. Still, as explained above, this solution is only second-best due to the distortion in the monopoly market for the private good caused by a positive emission tax. In Cases A and B, both periods are symmetric because pollution is a pure flow and, in the latter case, public abatement capital fully depreciates at the end of each period. Constant public abatement and tax rates are no longer optimal for depreciation rates smaller than one as seen in Case C (under a balanced budget rule) and Case D (if the regulator can issue public debt). Clearly, welfare is highest if the regulator can invest in a durable abatement technology and is allowed to maintain a budget deficit in the first period. This implies that budget institutions should consider exemptions from stability and deficit rules when public debt accumulation serves high early investments in abatement capital.

Naturally, these results have to be treated with caution. Since the parameter values were chosen arbitrarily, the numerical analysis merely illustrates the theoretical findings from above and does not provide a basis for policy advice on its own merits. This would require a calibration with empirically verifiable values. However, the sheer complexity of environmental and climate systems would generally require more elaborate functions which follow the lines of, for instance, Annicchiarico and

[26] The model with concave utility from g_t does not quite represent the literature benchmark with constant MCPF equal to $\lambda = 1$. However, the linear case is numerically not comparable to the concave model and, thus, neglected in Table 4.1.

Di Dio (2015) and Economides and Xepapadeas (2018) in DSGE models, Catalano et al. (2020) in an OLG model, or even the DICE model (Nordhaus, 2018) rather than the simple quadratic form in (4.21). Yet, for this very reason, these models only allow for numerical simulations, while their scope renders analytical analyses infeasible. As the focus of this chapter is on the theoretical model, I opted for a simplified numerical example. In Appendix 4.8.5, I provide some numerical intuition on how stock pollution affects these outcomes.

4.7 Conclusion

In this chapter, I employ the canonical baseline model of public incentives for firm-level abatement in a monopoly market as established by Barnett (1980) and expand it in three dimensions. First, I introduce fiscal policy considerations by acknowledging that the government may use emission tax revenues productively such that tax payments and revenues no longer cancel out in the regulator's welfare maximization problem. As a result, the optimal emission tax rate is no longer driven by just the environmental damage of emissions and efficiency concerns in the monopoly market for a private good, but also depends on funding requirements for public provision of goods or transfers. Second, in addition to the standard assumption that firms can abate emissions to avoid tax payments, the government is also able to invest in public abatement of emissions in my model. I show that, in this case, the regulator can attain the same (or even more ambitious) pollution targets at a lower tax rate which increases provision of the private good and improves overall welfare. Third, public abatement efforts are often long-term investments which can be utilized repeatedly, e.g., re-naturalization, water treatment facilities or, in the context of climate change, afforestation and CCS technologies. Therefore, I also expand the static model by considering durable public abatement capital in a two-period model. When the stock of public abatement capital depreciates slowly, it is optimal to invest more in abatement early on. Under a balanced budget rule, this is funded at the expense of lower provision of other public goods, e.g., a lower climate dividend. In contrast, if the regulator is able to issue public debt, tax revenues from later periods can be tapped to fund early public abatement and smooth provision of the public good over time. Thus, the model suggests that with durable abatement capital, budget deficits should be tolerated in order to maximize welfare. Since public abatement substitutes for taxation as a means to reduce pollution damages, durability can lead to increasing tax rates over time.

Recent contributions on public incentives for firm-level abatement mostly apply a single-period model and focus on issues of information asymmetry, imperfect compliance or the optimal timing of regulations. These models often contrast the efficiency of taxes with permit trading, emission caps or standards. Since the monopolist's decision to abate is continuous instead of binary and there are no timing issues in the framework of this chapter, a system where the regulator auctions off the optimal number of emission permits should produce the same results as derived above.[27] On the other hand, quotas or standards cannot be examined in this model as they are revenue-neutral (neglecting enforcement costs and revenues from fines).

Naturally, this model is subject to a number of limitations. First, the analytical results presented in Sections 4.4 and 4.5 are proven only for depreciation rates in the neighborhood of one. While the numerical analysis in Section 4.6 cannot substitute for a rigid formal derivation, it at least indicates that the results with regard to public abatement and optimal public debt may extend to all possible depreciation rates, whereas he effect of durable abatement capital on the tax rates largely depends on the parameterization of the problem. Similarly, due to the complex intertemporal interactions between tax rates, the stock of abatement capital and pollution, deriving effects in the presence of stock pollution is analytically not feasible.

Apart from analytical restrictions, it might also be argued that not just the government but also the firm should be able to invest in durable abatement capital. However, I deliberately choose this approach because firm-level emission abatement is often characterized by 'flow activities'. Industrial filters for air pollutants have to be replaced regularly, whereas waste or cooling water has to be continuously treated before being re-released into the water cycle. Of course, this does not account for the fact that producers can permanently shift to 'green' technologies or source renewable energy. In this regard, D'Amato and Dijkstra (2015) analyze a model where transitioning to a clean production technology requires upfront investments and emission taxes act as an incentive to adopt the new technology. Although D'Amato and Dijkstra are primarily interested in how the optimal emission tax is affected by imperfect information on firms' true adoption costs, their basic approach might be worthwhile to incorporate in the framework of this chapter. Furthermore, since emission taxes are often earmarked for spending on environmental services or transfers as 'climate dividends' to increase voters' acceptance of new taxes, I did not include other distortionary taxes, e.g., on labor or profits, as in the classic double-dividend literature. Consequently, the regulator's budget constraint should not be

[27] When firms are competitive and just decide whether to abate or not, Requate and Unold (2003) show that permit trading can be more efficient than taxes which may lead to over- or under-adoption of the green technology under an emission tax scheme.

interpreted as the government's full fiscal problem but rather a partial budget for environmental spending. Regardless, it could be instructive to also examine the effects of introducing an emission tax in the face of an already existing distortionary tax. This approach is taken by Bayindir-Upmann (2000) who analyzes a system with both taxes on emissions and capital, though under a simplified budget constraint and without public abatement. The general scarcity of both empirical and theoretical, contributions in the area of integrated fiscal and climate policy leaves ample opportunity for future research.

4.8 Appendix

4.8.1 Proof of Proposition 4.1

According to (4.8), the regulator should invest a positive amount in public abatement if, in the benchmark with $a = 0$ and $g = R(\tau)$,

$$\varphi'(0)D'\big[e(\tau)\big] > V'\big[R(\tau)\big]. \tag{4.27}$$

This condition is always met, if $\varphi(a)$ meets the Inada conditions. To show that the optimal emission tax rate decreases when $a > 0$ in comparison to the benchmark without public abatement, I employ

$$\widetilde{W}_\tau = -P'\big[q(\tau)\big]q'(\tau)q(\tau) - e(\tau) + \big[\varphi'(a)R'(\tau) - e'(\tau)\big]D'\big[e(\tau) - \varphi(a)\big] = 0, \tag{4.28}$$

which is obtained from substituting (4.2), (4.3) and (4.8) into (4.9). Starting from the status quo with $a = 0$ and exogenously increasing a, the marginal effect of public abatement investments on the tax rate can be derived by applying the Implicit Function Theorem to (4.28) which results in

$$\frac{\partial \tau}{\partial a} = -\frac{\widetilde{W}_{\tau a}}{\widetilde{W}_{\tau\tau}}, \tag{4.29}$$

where, using again that $V'(g) = \varphi'(a)D'\big[e(\tau) - \varphi(a)\big]$ from (4.8), the denominator equals

$$\begin{aligned}\widetilde{W}_{\tau\tau} &= -P''\big[q(\tau)\big]q'(\tau)^2 q(\tau) - P'\big[q(\tau)\big]q'(\tau)^2 - P'\big[q(\tau)\big]q''(\tau)q(\tau) - e'(\tau)\\ &\quad + \varphi'(a)D'\big[e(\tau - \varphi(a))\big]R''(\tau) + \varphi'(a)D''\big[e(\tau) - \varphi(a)\big]R'(\tau)e'(\tau)\\ &= W_{\tau\tau} - V''(g)R'(\tau)^2 + \varphi'(a)D''\big[e(\tau) - \varphi(a)\big]R'(\tau)e'(\tau). \qquad (4.30)\end{aligned}$$

The second-order condition $W_{\tau\tau}$ has to be negative in a welfare maximum. Hence, in the case with constant MCPF, i.e., $V''(g) = 0$, $\widetilde{W}_{\tau\tau}$ will also be negative for $R'(\tau) > 0$ because then the last term on the RHS of (4.30) is smaller than zero. In contrast, when the marginal utility of g is decreasing, i.e., $V''(g) < 0$, (4.30) is no longer unambiguously negative. Then, a sufficient condition for $\widetilde{W}_{\tau\tau} < 0$ is $\varphi' D'' e' < V'' R'$. The numerator in (4.29) can be derived as

$$\widetilde{W}_{\tau a} = \varphi''(a)D'\big[e(\tau) - \varphi(a)\big]R'(\tau) - \big[\varphi'(a)\big]^2 D''\big[\,\cdot\,\big]R'(\tau) + \varphi(a)D''\big[\,\cdot\,\big]e'(\tau), \qquad (4.31)$$

which is negative for all $R'(\tau) > 0$ regardless of the shape of $V(g)$. Hence, the optimal emission tax rate is decreasing in public abatement. ■

4.8.2 Proof of Proposition 4.2

The effects on first-period investments and the tax rates can be derived by means of Cramer's Rule which equals

$$\frac{\partial x}{\partial \delta} = \frac{|J_x|}{|J|}, \qquad \text{where } x \in \{a_1, \tau_1, \tau_2\}. \qquad (4.32)$$

The denominator $|J|$ represents the determinant of the Jacobian which coincides with the Hessian of the regulator's problem. In the welfare optimum, the Hessian has to be negative-definite which implies $|H| > 0$. Thus, the sign of the marginal effect is determined by the numerator on the RHS of (4.32). As argued above, the regulator will choose constant tax rates, τ, and abatement investments, a, in $\delta = 1$ which can be exploited to obtain the reduced expression

$$|J_{a_1}|\big|_{\delta=1} = -W_{\tau\tau}W_{a_1\delta}\big[W_{\tau\tau}W_{aa} - (W_{\tau a})^2\big], \qquad (4.33)$$

where $[W_{\tau\tau}W_{aa} - (W_{\tau a})^2]$ is the second principal minor of $|H|$ and, thus, positive in the welfare maximum. The second-order conditions $W_{\tau_t\tau_t} \equiv W_{\tau\tau} < 0$, $W_{a_t a_t} \equiv$

$W_{aa} < 0$ have to be negative in the welfare optimum. Moreover, the signs of the remaining cross-derivatives can be identified as

$$W_{\tau_t a_t} = \varphi'(a)e'(\tau)D''[e(\tau) - \varphi(a)] \equiv W_{\tau a} < 0 \tag{4.34}$$
$$W_{a_1\delta} = -\varphi'(a)D'[e(\tau) - \varphi(a)] < 0 \tag{4.35}$$
$$W_{a_2\delta} = -a\varphi''(a)D'[e(\tau) - \varphi(a)] + a\big(\varphi'(a)\big)^2 D''[e(\tau) - \varphi(a)] > 0 \tag{4.36}$$
$$W_{\tau_2\delta} = -a\varphi'(a)e'(\tau)D''[e(\tau) - \varphi(a)] > 0, \tag{4.37}$$

in the neighborhood of $\delta = 1$ such that $\partial a_1/\partial\delta|_{\delta=1} < 0$ which proofs part (i). Analogously, the numerators for the marginal effects on τ_1 and τ_2 can be derived as

$$|J_{\tau_1}|\big|_{\delta=1} = W_{\tau a}W_{a_1\delta}\big[W_{\tau\tau}W_{aa} - (W_{\tau a})^2\big] > 0, \tag{4.38}$$
$$|J_{\tau_2}|\big|_{\delta=1} = \big(W_{a_2\delta}W_{\tau a} - W_{aa}W_{\tau_2\delta}\big)\big[W_{\tau\tau}W_{aa} - (W_{\tau a})^2\big], \tag{4.39}$$

where the term in parentheses in (4.39) becomes zero under the conditions of part (ii), i.e., for constant MCPF, i.e., $V'(g_t) \equiv \lambda$. Hence, $\partial\tau_1/\partial\delta|_{\delta=1} > 0$ and $\partial\tau_2/\partial\delta|_{\delta=1} = 0$.

For decreasing marginal utility, i.e., $V''(g_t) < 0$, in part (iii), the sign of the cross-derivate

$$W_{\tau a} = -V''(g)R'(\tau) + \varphi'(a)e'(\tau)D''[e(\tau) - \varphi(a)] \gtrless 0, \tag{4.40}$$

is no longer unambiguous for tax rates on the increasing side of the Laffer curve, but becomes negative [positive] if V' decreases slowly [fast] enough, i.e., if $-V''(g)$ is low [high], i.e., $\varphi'e'D'' <$ [>]$V''R'$. Then, the sign of (4.38) is positive [negative] such that $\partial\tau_1/\partial\delta|_{\delta=1} >$ [<]0. Due to the change in (4.40), the term in square brackets in (4.39) no longer equals zero but becomes positive for $R'(\tau) > 0$. As a result, $\partial\tau_2/\partial\delta|_{\delta=1} > 0$ which concludes the proof of part (iii). ■

4.8.3 Proof of Proposition 4.3

Again, parts (i) and (ii) of Proposition 4.3 can be derived by use of Cramer's Rule. As public debt, b, and provision of the public good, g, are expressed as functions of the tax rates and abatement efforts, the Hessian is still a 4-by-4 matrix such that the denominator of

$$\frac{\partial x}{\partial\delta} = \frac{|J_x|}{|J|}, \qquad \text{where } x \in \{a_1, a_2, \tau_1, \tau_2\}. \tag{4.41}$$

has to be positive in the optimum. With the ability to issue public debt, the respective numerators of (4.41) follow as

$$|J_{a_1}|\big|_{\delta=1} = W_{a_1\delta}B + W_{a_2\delta}A + W_{\tau_2\delta}C, \tag{4.42}$$
$$|J_{a_2}|\big|_{\delta=1} = W_{a_1\delta}A + W_{a_2\delta}B + W_{\tau_2\delta}D, \tag{4.43}$$
$$|J_{\tau_1}|\big|_{\delta=1} = W_{a_1\delta}D + W_{a_2\delta}C + W_{\tau_2\delta}E, \tag{4.44}$$
$$|J_{\tau_2}|\big|_{\delta=1} = W_{a_1\delta}C + W_{a_2\delta}D + W_{\tau_2\delta}F, \tag{4.45}$$

where terms A through F equal

$$\begin{aligned}
A &= W_{a_ia_j}\left(W_{\tau\tau}^2 - W_{\tau_i\tau_j}^2\right) + W_{\tau_i\tau_j}\left(W_{\tau_ia_i}^2 + W_{\tau_ia_j}^2\right) - 2W_{\tau\tau}W_{\tau_ia_i}W_{\tau_ia_j},\\
B &= -\left\{W_{aa}W_{\tau\tau}^2 + 2W_{\tau_ia_i}W_{\tau_ia_j}W_{\tau_i\tau_j} - W_{\tau\tau}\left(W_{\tau_ia_i}^2 + W_{\tau_ia_j}^2\right) - W_{aa}W_{\tau_i\tau_j}^2\right\},\\
C &= W_{\tau_ia_j}\left(W_{aa}W_{\tau\tau} - W_{\tau_ia_j}^2\right) + W_{\tau_ia_j}W_{\tau_ia_i}^2\\
&\qquad + W_{\tau_i\tau_j}W_{\tau_ia_j}W_{a_ia_j} - W_{\tau_ia_i}\left(W_{aa}W_{\tau_i\tau_j} + W_{a_ia_j}W_{\tau\tau}\right),\\
D &= W_{\tau_ia_i}\left(W_{aa}W_{\tau\tau} - W_{\tau_ia_i}^2\right) + W_{\tau_ia_i}\left(W_{a_ia_j}W_{\tau_i\tau_j} + W_{\tau_ia_j}^2\right)\\
&\qquad\qquad - W_{\tau_ia_j}\left(W_{aa}W_{\tau_i\tau_j} + W_{\tau\tau}W_{a_ia_j}\right),\\
E &= W_{\tau_i\tau_j}\left(W_{aa}^2 - W_{a_ia_j}^2\right) + W_{a_ia_j}\left(W_{\tau_ia_i}^2 + W_{\tau_ia_j}^2\right) - 2W_{aa}W_{\tau_ia_i}W_{\tau_ia_j},\\
F &= -\left\{W_{\tau\tau}W_{aa}^2 - W_{aa}\left(W_{\tau_ia_i}^2 + W_{\tau_ia_j}^2\right) - W_{a_ia_j}\left(W_{\tau\tau}W_{a_ia_j} - 2W_{\tau_ia_i}W_{\tau_ia_j}\right)\right\},
\end{aligned}$$

with $i, j \in \{1, 2\}$, $i \neq j$, $W_{a_1\delta} < 0$ and $W_{a_2\delta}, W_{\tau_2\delta} > 0$ in the neighborhood of $\delta = 1$ as in the proof of Proposition 4.2. In the case at hand, the Jacobian is equal to the Hessian. The latter has to be negative-definite in the welfare maximum, implying that its principal minors have to alter in sign commencing with $|H_1| < 0$. Furthermore, the Hessian can be arranged in various ways such that B and F are both equal to the Hessian's third principal minor multiplied by -1. Thus, $|H_3| < 0$ implies that B and F are always positive. In contrast, the first terms in parentheses in A, C, D and E are equal to the second principal minor of the Hessian, $|H_2| > 0$ and, thus, all have to be positive in the optimum. Therefore,

$$W_{\tau a} = -0.5V''(g)R'(\tau) + \varphi'(a)e'(\tau)D''[e(\tau) - \varphi(a)] < 0, \tag{4.46}$$

is a sufficient condition to ensure that $C > 0$ and $A, D, E < 0$. Similar to part (iii) of Proposition 4.2, this is fulfilled whenever the (absolute) curvature of $V(g)$, i.e., $-V''(g)$ is sufficiently close to zero. Then, each of the last terms on the RHS of equations (4.42) to (4.45) has the opposite sign of the first two terms. Since in all four expressions, the last term is weighted by $W_{\tau_2\delta}$, the sign of the full expressions

A, C, D and E equals the common sign of the first two summands on the RHS if $W_{\tau_2\delta}$ is sufficiently close to zero. In this case, $|J_{a_1}|, |J_{\tau_2}| < 0$ and $|J_{a_2}|, |J_{\tau_1}| > 0$. Consequently, $\partial a_1/\partial\delta, \partial\tau_2/\partial\delta < 0$, whereas $\partial a_2/\partial\delta, \partial\tau_1/\partial\delta > 0$ at $\delta = 1$.

To prove part (iii) of Proposition 4.3, the two budget constraints in (4.16) can also be combined to derive the optimal level of public debt as

$$b = \frac{g_1 - g_2}{2} + \frac{a_1 - a_2}{2} - \frac{R(\tau_1) - R(\tau_2)}{2}. \tag{4.47}$$

From (4.17), it follows that provision of the public good is constant. Therefore, the first term on the RHS of (4.47) cancels out in the welfare maximum. Furthermore, as durability improves starting from $\delta = 1$, parts (i) and (ii) imply that $a_1 > a_2$ and $R(\tau_1) < R(\tau_2)$ such that the sum on the RHS of (4.47) is positive for marginal durability gains. ■

4.8.4 Derivation of u-shaped tax rates over depreciation rate

While the ability to issue public debt drives an initially increasing wedge between the tax rates for high depreciation rates, the opposite effect occurs as δ approaches zero. This can be verified by examination of the regulator's problem in $\delta = 0$. If public abatement capital does not depreciate at all, the welfare maximum is reached in a corner solution with $a_2 = 0$. Since first-period investments in the stock of abatement capital are just as productive in the first as in any subsequent period, there is no reason to invest in $t = 2$. Instead, the regulator will shift all revenues from second-period taxation that are not spent on provision of the public good, g_2, to the first period by means of public debt. Thus, for $\delta = 0$, the optimum is reached by maximizing W over just the tax rates, τ_1 and τ_2, and first-period investments in the stock of public abatement capital, a_1, whereas $a_2 = 0$ and the optimal values of b and g_t are defined implicitly.

Lemma 4.1 *If public abatement capital does not depreciate at all, the regulator levies a constant tax rate $\tau \equiv \tau_1 = \tau_2$ and provides constant quantities of the public good $g \equiv g_1 = g_2$ in both periods such that optimal public debt is equal to $b = a_1/2$. Thus, there exists a depreciation rate $\tilde{\delta} \in (0, 1)$ for which the wedge between the tax rates, τ_1 and τ_2, becomes maximal.*

Proof. If $\delta = 0$, the first-order conditions with regard to the three remaining explicit decision variables are given by

$$\begin{aligned} W_{\tau_t} =& \big[P'\big(q(\tau_t)\big) - C_q\big(q(\tau_t), e(\tau_t)\big)\big] q'(\tau_t) - e(\tau_t) \\ & \qquad + V'\big[\big(R(\tau_1) + R(\tau_2) - a_1\big)/2\big] R'(\tau_t) \\ & \qquad\qquad - e'(\tau_t) D'\big[e(\tau_t) - \varphi(a_1)\big] = 0 \quad \forall t, \end{aligned} \tag{4.48}$$

$$\begin{aligned} W_{a_1} =& - V'\big[\big(R(\tau_1) + R(\tau_2) - a_1\big)/2\big] \\ & + \varphi'(a_1)\big[D'\big(e(\tau_1) - \varphi(a_1)\big) + D'\big(e(\tau_2) - \varphi(a_1)\big)\big] = 0. \end{aligned} \tag{4.49}$$

Condition (4.48) can be solved for $V'(\cdot)$ to obtain

$$V'\big[\big(R(\tau_1) + R(\tau_2) - a_1\big)/2\big] = \Upsilon(\tau_t, a_1), \tag{4.50}$$

which may be substituted into (4.49). This shows that τ_1 has to be equal to τ_2, otherwise $\Upsilon(\tau_1, a_1) \neq \Upsilon(\tau_2, a_1)$. In order to fulfill (4.49), $\Upsilon(\tau_t, a_1)$ has to take a unique value which implies that τ_t must not vary between periods. Thus, given constant tax rates and $a_2 = 0$, optimal provision of the public good, $g_t = R(\tau) - a_1/2$, in both periods t and public debt, $b = a_1/2$, follow from (4.19) and (4.47), respectively.

If the regulator can accumulate public debt, it is optimal to levy constant tax rates across periods in both cases, when public abatement capital completely depreciates after one period ($\delta = 1$) and when investments can be used indefinitely long ($\delta = 0$.) This means that at least one tax rate has to be (inversely) u-shaped in δ if the tax rates initially diverge for durability improvements but then converge again as the depreciation rate approaches zero. ■

Lemma 4.1 qualifies Proposition 4.3 regarding the effects on the tax rates. Nonetheless, it is optimal to issue a positive amount of public debt for depreciation rates smaller than one. Lemma 4.1 crucially depends on the regulator's ability to accumulate debt at the end of the first period. Under a balanced budget rule, all second-period tax revenues that exceed the optimal spending on provision of the public good, g_2, have to be invested in abatement capital, a_2, even if increasing a_1 at the cost of a_2 would be preferable in $\delta = 0$. Therefore, the stock of public abatement capital will generally be larger in the second period and it is not optimal to levy a constant tax rate but rather $\tau_2 < \tau_1$ even if public abatement capital is perfectly durable.

4.8.5 The impact of stock pollution

Especially in the context of climate policy analysis, it is not always sensible to assume that pollution is a pure flow variable. Rather, pollution can also accumulate as a gradually decaying stock. This is the case for greenhouse gas emissions which have decay rates close to zero. Since stock pollutants introduce an additional interaction between first- and second-period decision variables, it is no longer possible to derive meaningful analytical results for this scenario. The tractability of the findings above hinges on the symmetric optima in $\delta = 0$ (except for $a_1 > a_2 = 0$) and $\delta = 1$ which only occur if pollution is a flow. For persistence rates $\gamma > 0$ and assuming that the inherited stock of pollution at the beginning of the first period is zero, the total intertemporal welfare damage from emissions is

$$D\Big(e(\tau_1) - \varphi(a_1)\Big) + D\Big(e(\tau_2) + \gamma e(\tau_1) - \varphi\big(a_2 + (1-\delta)a_1\big)\Big). \tag{4.51}$$

Hence, in the first-order condition with regard to τ_1, there is an additional incentive, $-\gamma e'(\tau_1) D_2' > 0$, to increase first-period taxation as emissions cause pollution damages and decrease welfare not only in the first but also subsequent periods. To the best of my knowledge, the only theoretical contributions which provide some evidence in this context are by Benchekroun and Van Long (1998) who examine the effect of stock pollution on the optimal emission tax in an oligopoly market and Chapter 2 where we introduce public adaptation spending in a tax smoothing framework. While the former contribution neither considers fiscal constraints nor public abatement efforts, the latter focuses on consumption decisions and ignores the production process including firm-level abatement. Hence, it seems expedient to provide at least some numerical intuition on the effect of stock pollutants.

To be consistent with the specification of depreciation rates above, Figure 4.2 depicts the welfare maximizing public decisions as functions of the emission decay rate, $(1-\gamma)$, instead of just γ. Thus, emission persistence increases from right to left in each of the panels in Figure 4.2 with the right-most point, $(1-\gamma) = 1$, representing the setting with pure flow pollution. The underlying numerical computations are based on the parameter specification $\{\alpha, \beta, c_q, c_a, d, \theta\} = \{10, 1, 0.5, 0.5, 0.6, 0.3\}$ and δ ranging over $\{0, 0.5, 1\}$ from panel (i) to (iii). While the frequently changing slopes of the graphs illustrate why it is not possible to derive conclusive analytical results for this case, some insight may still be gained from Figure 4.2. For one, the first-period emission tax rate appears to increase steadily as the stock of pollution becomes more persistent regardless of the durability of public abatement capital.

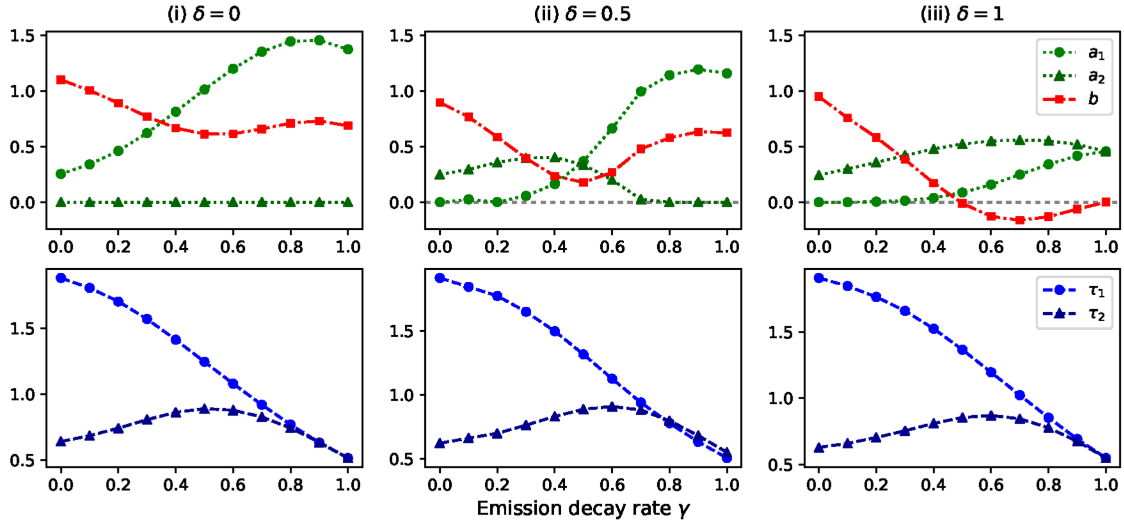

Figure 4.2: Welfare-maximizing outcomes with persistent stock pollution

In contrast, first-period abatement efforts overall decrease in emission persistence (even if a_1 can initially increase for high decay rates).

These two observations are closely linked to the shape of the public debt curve. As first-period emissions become more harmful in γ, the regulator imposes a higher tax rate, τ_1, to encourage firm-level abatement. If tax rates are initially located on the increasing side of the Laffer curve, this generates additional public revenues. Further, it might warrant lower investments, a_1, because a higher tax reduces emission damages immediately. Both effects imply that the need to shift funds between periods by the means of public debt decreases. However, the direction of the first effect changes if τ_1 increases beyond the maximum of the Laffer curve. For instance, in the point $\{\delta, \gamma\} = \{1, 0.7\}$ the slope of the Laffer curve in the optimal first-period tax rate is $R'(\tau_1) = -3.561$. Increasing τ_1 any further – which is welfare-maximizing if emissions become even more persistent – reduces revenues from first-period taxation. As first-period tax revenues shrink, the regulator has to resort to issuing public debt again for funding abatement, a_1, and ensuring a constant provision of the public good, $g_1 = g_2$. Depicted by panel (iii) in Figure 4.2, these dynamics can even result in a negative level of public debt, i.e., public savings, if emission decay rates are high, which turns into positive debt, $b > 0$, for relatively persistent emissions. Therefore, a balanced budget is no longer optimal in the presence of stock pollutants even if public abatement capital is not durable ($\delta = 1$). This result provides additional ground for the claim that welfare improves when non-revenue-neutral climate policy does not have to abide by a balanced budget rule.

Chapter 5

Concluding remarks

This dissertation consists of three contributions which analyze fiscal policy, specifically public debt management and government spending, as well as climate policy objectives in integrated partial-equilibrium models. While Chapters 2 and 4 examine how normative theory may justify deviations from a balanced budget rule in the presence of pollution externalities, Chapter 3 explores the positive effects on strategic decisions in a voting economy.

In the first analysis, we introduce a stock pollutant which stems from consumption of a private good and decays gradually over time in the standard tax smoothing framework. We show that, if the government can levy an emission tax on the polluting private good, it is optimal to charge a higher tax rate in the period where emissions are more harmful. Non-constant taxation implies that it cannot be optimal to maintain a balanced budget even if public spending remains constant over time. Whether the government should issue debt or accumulate savings is contingent on how tax revenues react to a tax increase and how emission damages evolve over time. In the context of climate change, this would most likely lead to a higher tax burden in the present. The emission tax is subject to a trade-off between minimizing the excess burden of taxation and reaching the efficient level of pollution internalization. We find that this conflict is alleviated if the government can invest tax revenues in adaptation technologies.

In the second contribution, I conduct a political economy analysis of strategic incentives when reelection of the incumbent government is uncertain. When politicians do not agree on how much pollution should be internalized, the incumbent issues more debt than under certain reelection in order to limit the future government's spending discretion. Since deviating from a balanced budget is normatively justified when pollution is a persistent stock, strategic debt can improve budget efficiency. Under the assumption that the government provides both polluting and clean public goods, I derive that reelection uncertainty also creates an incentive to cut provision of the polluting good in the present regardless of the incumbent government's environmental preferences. Moreover, competition from green parties can lead to additional emission abatement in the future. Hence, this paper shows that voting uncertainty entails three potential avenues for welfare gains from strategic interactions in the presence of stock pollution which were previously not captured by political economy models restricted to fiscal effects.

The final essay of this dissertation is based on the canonical model of second-best emission taxation in a monopoly market where I incorporate fiscal policy constraints. I assume that the government is not limited to refunding revenues from the emission tax as welfare-neutral lump-sum transfers but spends revenues productively on the provision of a public good or investments in abatement. In this framework, it is always optimal to partially substitute abatement conducted by the monopolist with public abatement spending and to levy a lower emission tax rate. While this can result in lower tax revenues, production in the monopoly market becomes more efficient which leads to a welfare gain. Additionally, if public abatement is durable, a balanced budget rule is no longer optimal and the government should be allowed to issue bonds in the first period.

To conclude, this dissertation contributes to the emerging literature bridging the gap between fiscal policy analyses and environmental economics. By taking an integrated approach to address both topics, the analytical models presented in this dissertation show that emission tax schedules should dynamically adjust over time to account for persistent stock pollution and public engagement in abatement technologies. Consequently, adhering to a balanced budget rule is generally no longer optimal under these conditions. Whether this result is tantamount to a normative justification for higher public borrowing, is contingent on a number of factors including how fast emissions decay and the specifics of the abatement technologies available to the government. At the same time, the positive analysis of strategic incentives reveals that budget institutions may still be necessary to prevent excessive deficit spending depending on the political status quo.

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